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PAVE LOW - EVALUATION OF A TERRAIN FOLLOWING RADAR SYSTEM FOR THE HH-53 HELICOPTER

AFFTC

RICHARD H. BOIVIN
Lieutenant Colonel, USAF
Project Engineer

JOHN SCHMIDT
Major, USAF
Systems Engineer

PAUL J. BALFE
Major, USAF
Project Officer/
Project Pilot

TECHNICAL REPORT No. 73-11

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Distribution limited to U.S. Government agencies only (Test and Evaluation), February 1973. Other requests for this document must be referred to ASD/SDQH, Wright-Patterson AFB, Ohio 45433.

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

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FOREWORD

This report contains a functional evaluation of a manual terrain following radar system installed on an HH-53B helicopter for search and rescue applications. The report also includes a functional evaluation of modifications to a previously developed limited night recovery system (LNRS). The PAVE LOW test and evaluation program began on 28 April 1972 at the AFFTC and was concluded on 3 December 1972.

Test authority for the program was AFR 80-14 and AFFTC Project Directive 71-97. Participating agencies were Aeronautical Systems Division (ASD), Military Airlift Command (MAC)/Aerospace Rescue and Recovery Service (ARRS), and Norden Division of United Aircraft.

Foreign announcement and dissemination by the Defense Documentation Center are not authorized because of technology restrictions of the U.S. Export Control Acts as implemented by AFR 400-10.

Prepared by:

Richard H. Boivin

RICHARD H. BOIVIN
Lieutenant Colonel, USAF
Project Engineer

John Schmidt

JOHN SCHMIDT
Major, USAF
Systems Engineer

Paul J. Balfe

PAUL J. BALFE
Major, USAF
Project Officer/
Project Pilot

Reviewed and approved by:
13 March 1973

James W. Wood

JAMES W. WOOD
Colonel, USAF
Deputy Commander for Operations

Howard M. Lane

HOWARD M. LANE
Brigadier General, USAF
Commander

ABSTRACT

This report presents the results of a flight test and evaluation program of a prototype terrain following/terrain avoidance (TF/TA) radar system for search and rescue applications installed on an HH-53B helicopter. The report also presents an evaluation of the addition of symbology to the low light level television (LLLTV) display installed as part of the limited night recovery system (LNRS) in the same aircraft. The symbology addition to the LLLTV display made a significant improvement to the existing LNRS system. Pilot workload was reduced and the symbology promoted increased pilot confidence and allowed much more precise hover control. The overall impression of the TF/TA radar was that it provided increased capability to perform the night recovery mission. The shades of gray display provided as part of the PAVE LOW program, was exceptionally well suited to the manual terrain following and terrain avoidance mission. However, numerous deficiencies in this preliminary prototype terrain following radar (TFR) system were not corrected because of the limited time and funds available. Among the discrepancies were: insufficient terrain clearance over obstacles, a descent rate that was too slow, insufficient horizontal clearance to obstacles, inability to operate in adverse weather and over certain terrain conditions, and an unsatisfactory failure detection and warning system. Further development and testing is required before a production model system can be achieved.

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Item	Definition
AGL	above ground level
ARRS	Aerospace Rescue and Recovery Service
ASD	Aeronautical Systems Division
fpm	feet per minute
GM	ground map
HSD	horizontal situation display
IOT&E	Initial Operational Test and Evaluation
LLLTV	low light level television
LNRS	limited night recovery system
MAC	Military Airlift Command
ROC	Required Operational Capability
TA	terrain avoidance
TC	terrain clearance
TF	terrain following
TFR	terrain following radar
TFRIS	terrain following radar instrumentation system
TF/TA	terrain following/terrain avoidance
VSD	vertical situation display

INTRODUCTION

GENERAL

The MAC Required Operational Capability (ROC) 19-70 established the requirement for a terrain avoidance (TA) and terrain following (TF) radar system to be developed for the ARRS. ARRS required the capability to fly at low level over hostile territory at night and in periods of adverse weather. The PAVE LOW program was initiated to develop that capability. The primary objective of the PAVE LOW program, as directed by ASD, was to investigate the capabilities and limitations of a modified AN/APQ-141 radar system in a manual terrain following/terrain avoidance configuration installed in an HH-53B helicopter equipped with the limited night recovery system (LNRS). A secondary objective of the test program was to evaluate the addition of electronically generated symbology to a low light level television display (LLLTV) previously developed for use on the HH-53B as part of an LNRS. The aircraft used in the test program was an HH-53B serial number 66-14433.

The initial portion of the test program, from 28 April 1972 through 3 November 1972, was devoted to development of the radar by the Norden Division of United Aircraft and only a very limited evaluation by the AFFTC during the development stage. The Norden development effort was terminated on 31 October 1972 to allow an Air Force evaluation even though there were known deficiencies that could have been corrected with additional time. Initial Operational Test and Evaluation (IOT&E) flights were conducted by MAC/ARRS personnel from 6 through 10 November 1972 and from 19 through 22 November 1972. An evaluation by the AFFTC was conducted from 15 through 17 November 1972 and from 27 November through 1 December 1972. The entire development test and evaluation program consisted of 73 flights and 100.2 flying hours. A summary of the missions flown is included in appendix I.

The AN/APQ-141 radar was originally designed for the Army Cheyenne helicopter program. The Air Force obtained the loan of this equipment for the PAVE LOW Program. Redesign of the AN/APQ-141 radar for the PAVE LOW program was purposely kept to a minimum. Some of the deficiencies reported are a result of minimizing the design changes. Some other deficiencies in the performance of the radar should have been corrected for this evaluation, but development of the system was continually delayed by Doppler radar malfunctions. Development was terminated on 31 October 1972, precluding correction of those discrepancies.

PAVE LOW SYSTEM DESCRIPTION

The PAVE LOW system tested is shown in a simplified functional diagram in figure 1. The heart of the system was the AN/APQ-141 terrain following/terrain avoidance (TF/TA) radar. The radar measured range and elevation angle to the surrounding terrain and combined this information with ground speed, drift, and vertical velocity to produce a manual terrain following command signal, an aircraft velocity vector signal, and a contour mapping type of display on the vertical situation display (VSD) indicator. The symbol generator system received ground speed, drift, and vertical velocity from the Doppler radar and altitude from the radar altimeter. These inputs were combined with attitude information from the vertical gyro to provide an integrated television display of the camera video with appropriate symbology superimposed to aid in hovering precisely over a desired location.

Modified AN/APQ-141 Radar

The AN/APQ-141 radar, the horizontal situation display (HSD), and the VSD were all originally designed for the Army AH-56 Cheyenne weapon system. Norden division of United Aircraft provided the engineering and modification necessary for the radar system to perform terrain avoidance and terrain following without the digital computer that was an inherent part of the Cheyenne system. The AN/APQ-141 radar consisted of the following line replaceable units:

1. antenna
2. receiver
3. data processor unit
4. transmitter/modulator
5. control box

The antenna used a phase interferometer technique to determine the elevation angle to a particular target return. This allowed the antenna to provide rapid and accurate elevation angle information and still be small enough to be housed in a limited space. The data processor contained the manual terrain following computer which provided the computation of the terrain following command. The terrain following computer generated a template representative of the intended terrain following profile. This template was designed for a ground speed of 120 knots and is shown in figure 2. The TF/TA radar measured elevation and range to the terrain ahead of the aircraft. It should be noted that for every range there was a particular elevation angle to the template. A climb was commanded whenever an elevation angle equal to or greater than that of the template was detected. The radar video containing the elevation information as a function of range was referred to as phase video to differentiate it from the normal search video which contained amplitude information as a function of range. Phase video was routed to the VSD and search video to the HSD. Table I lists some of the AN/APQ-141 parameters.

Table I

AN/APQ-141 RADAR CHARACTERISTICS

Transmitted power	30 kw minimum
Elevation coverage	±30 deg
Azimuth beam width	2.0 deg
Azimuth scan	±45 deg
Azimuth scan rate	50/175 deg per sec
Polarization	horizontal
Antenna stabilization	No
Frequency agility	Yes
Antenna gain	22.6 db
Weight	132 lb
Power 30, 400 cps	980 va
Power 28 vdc	2 amps
Frequency	Ku band

Vertical Situation Display

The VSD processed the phase video signal to provide a "shades of gray" display of elevation versus azimuth. The display size was 5 inches by 7 inches and provided a coverage of ±27 degrees in elevation and ±36 degrees in azimuth. The VSD is represented in figure 3. The darkest section shown at the bottom of the display represented the first quarter mile of range from the aircraft. The contour line thus portrayed represented the maximum elevation angle of the terrain within that quarter mile range. The next darkest contour represented the maximum elevation angle to the terrain in the range from 1/4 to 1/2 mile in front of the aircraft. This scheme continued with progressively lighter shades of gray used to portray similar contours at 1 mile, 2 1/2 miles, and 5 miles. A contour select knob allowed the pilot to select one of the contours to be highlighted by a dashed line. In the figure shown, the 1-mile range contour has been selected. A roll angle indicator and scale was provided across the bottom of the display. A horizon line was also displayed to aid the pilot as a reference for roll, climb and dive information. The terrain following command vector was displayed as a square (□). The aircraft velocity vector was displayed as a cross (+). An aircraft symbol was etched on the glass in the center of the display. This symbol, combined with the horizon and roll markers, served as an attitude indicator.

The command vector and velocity vector were displaced from the center to account for crosswind effect and indicated the true track of the aircraft. The display allowed for up to 25 degrees of drift and the two symbols blinked if there were 25 or more degrees of drift indicated. For manual terrain following the pilot attempted to keep the velocity vector symbol (+) centered with the command vector symbol (□).

Horizontal Situation Display

The HSD presented search video in a depressed center plan position indicator format. The display had an azimuth coverage of 45 degrees either side of the aircraft heading. Drift information from the Doppler radar was utilized to generate a strobe representing the track of the aircraft. Range marks appropriate to the range selected were displayed as arcs. The HSD could be operated in either of two modes, ground map (GM) mode or terrain clearance (TC) mode. In the GM mode, the search video from all the terrain within the selected range was displayed. In the TC mode, only radar returns from targets above the boresight angle were displayed. The boresight angle corresponded approximately with the longitudinal axis of the aircraft. Thus if the aircraft were in a horizontal attitude, radar returns from all terrain below the aircraft altitude would not be displayed in the TC mode. The only returns displayed under that condition would be from targets at an altitude equal to or higher than that of the aircraft.

Low Light Level Television Symbology

The LLLTV was equipped with a special symbology presentation during the PAVE LOW program. The symbol generation system interfaced with other elements of the PAVE LOW system as shown in figure 1. The symbology was available on the LLLTV in two different modes of operation, search and hover. The LLLTV symbology format is portrayed in figures 4 and 5.

The search mode presented ground speed, radar altitude, and camera angle in numeric form located near the corners of the LLLTV screen.

Vertical velocity information derived from the Doppler radar was displayed on the right edge in a logarithmic scale. Roll angle was displayed along the top of the LLLTV screen. A horizon line, flight path vector (cross), and camera bore sight (1/4-inch solid white square) were also presented on the screen. The velocity vector indicated where the aircraft would impact if the current flight path were continued.

The hover mode display included ground speed, radar altitude, camera boresight angle, and the camera boresight symbol in the same manner as in the search mode. A square box symbol portrayed the true vertical from the helicopter to the ground and represented the impact point for the hoist. A velocity vector (cross) was displayed that gave an indication of ground speed in both lateral and longitudinal directions. A correct hover resulted in the cross and the desired hoist impact point being displayed inside the box.

EQUIPMENT INSTALLATION

A prime consideration of the PAVE LOW equipment installation was to perform a minimum of modifications to the helicopter. The equipment locations chosen were not intended to be a final configuration, but were chosen for ease of installation and removal as well as suitability for operation. Figure 6 shows the general locations of the modifications performed. The aerial refueling probe was removed and a radome was installed in its place. The radome housed the antenna, transmitter and receiver of the AN/APQ-141 radar. This installation is shown in figure 7.

The VSD and HSD were mounted on the copilot's side of the instrument panel as shown in figure 8. This installation again was a minimum modification and resulted in the copilot's heading indicator being removed along with several other instruments that would be necessary in an operational aircraft. The radar control panel was installed on the left side of the center console as shown in figure 9. The LLLTV monito was left in its original position on the pilot's instrument panel as shown in figure 10. The LLLTV camera/symbology control panel was located on the forward right side of the lower console.

A work table and equipment rack were installed in the left side of the cabin to mount the radar data processor, VSD generator, vertical gyro, power panel with circuit breakers, and the majority of the special instrumentation equipment. This installation of the instrumentation/radar table is shown in figure 11.

The instrumentation equipment installed inside the aircraft consisted of a Sony television camera, video recorder, television monitor and an oscillograph. A terrain following instrumentation system (TFRIS) was installed on the left sponsor. Appendix II contains more detailed information on the instrumentation system.

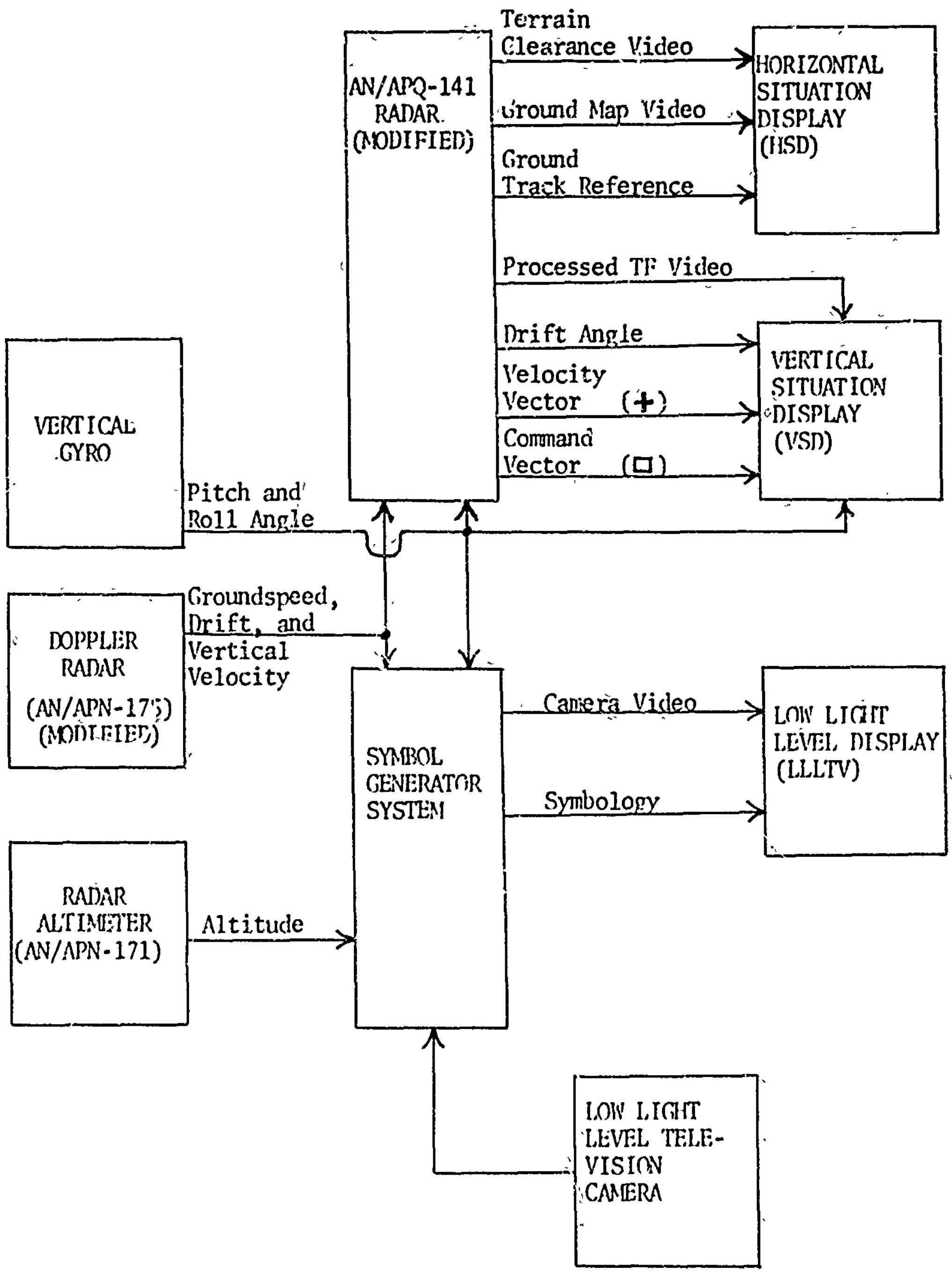


Figure 1 PAVE LOW Simplified System Diagram

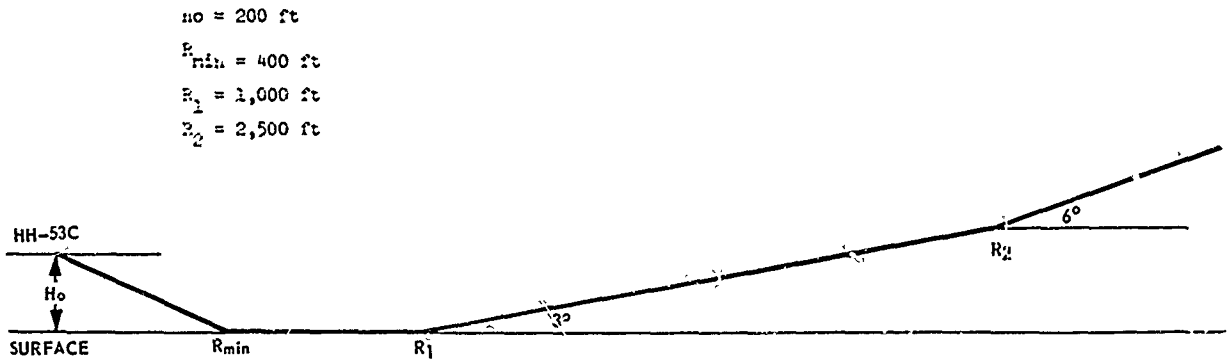


Figure 2   Terrain Following Template

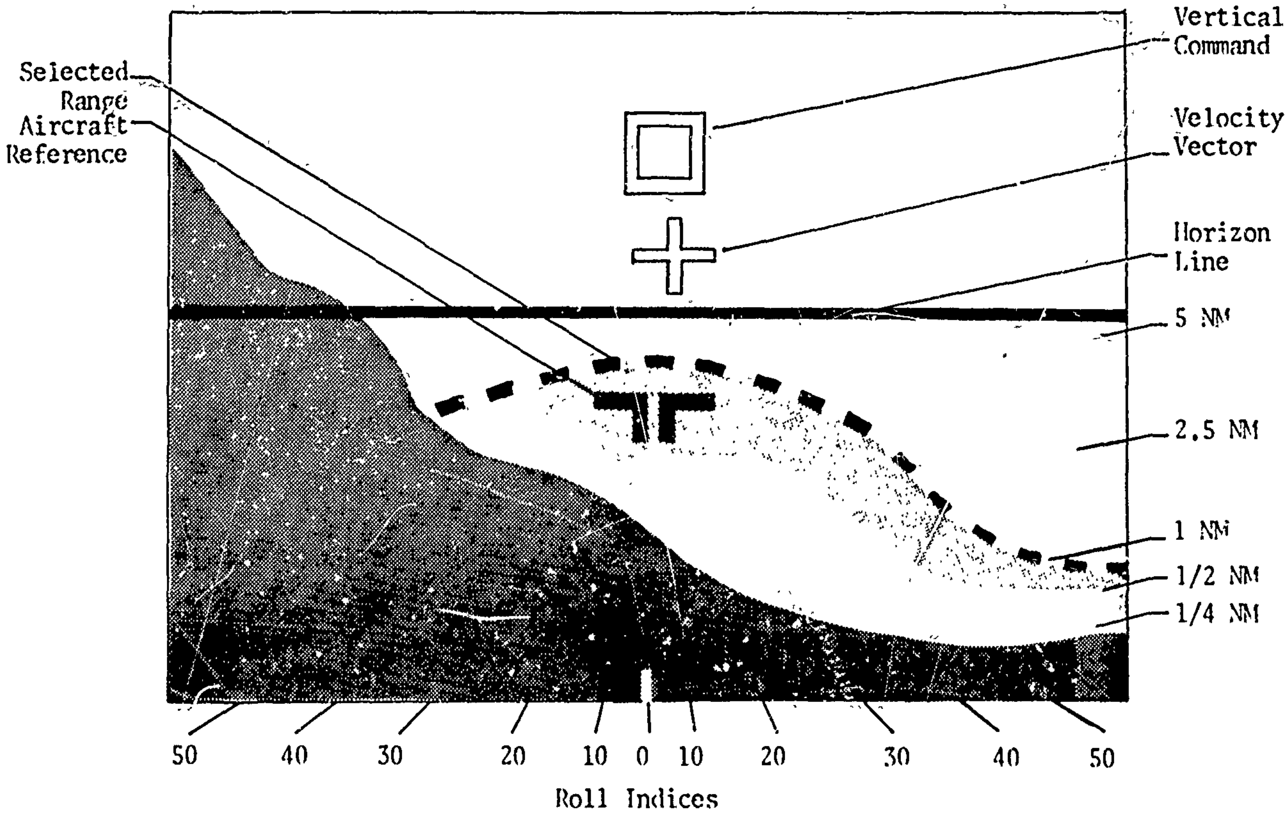


Figure 3   Vertical Situation Display

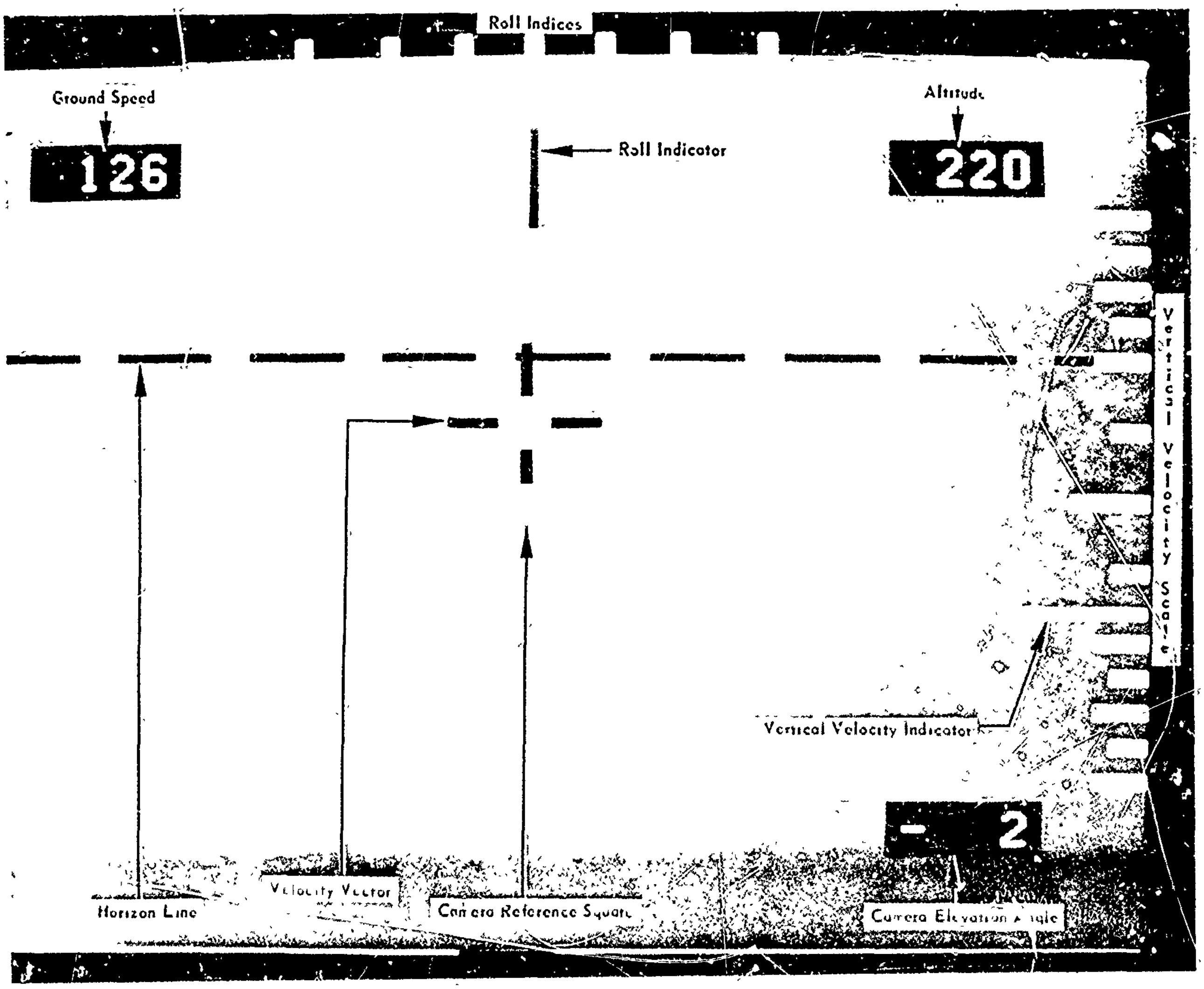


Figure 4 Low Light Level Television Display Search Mode

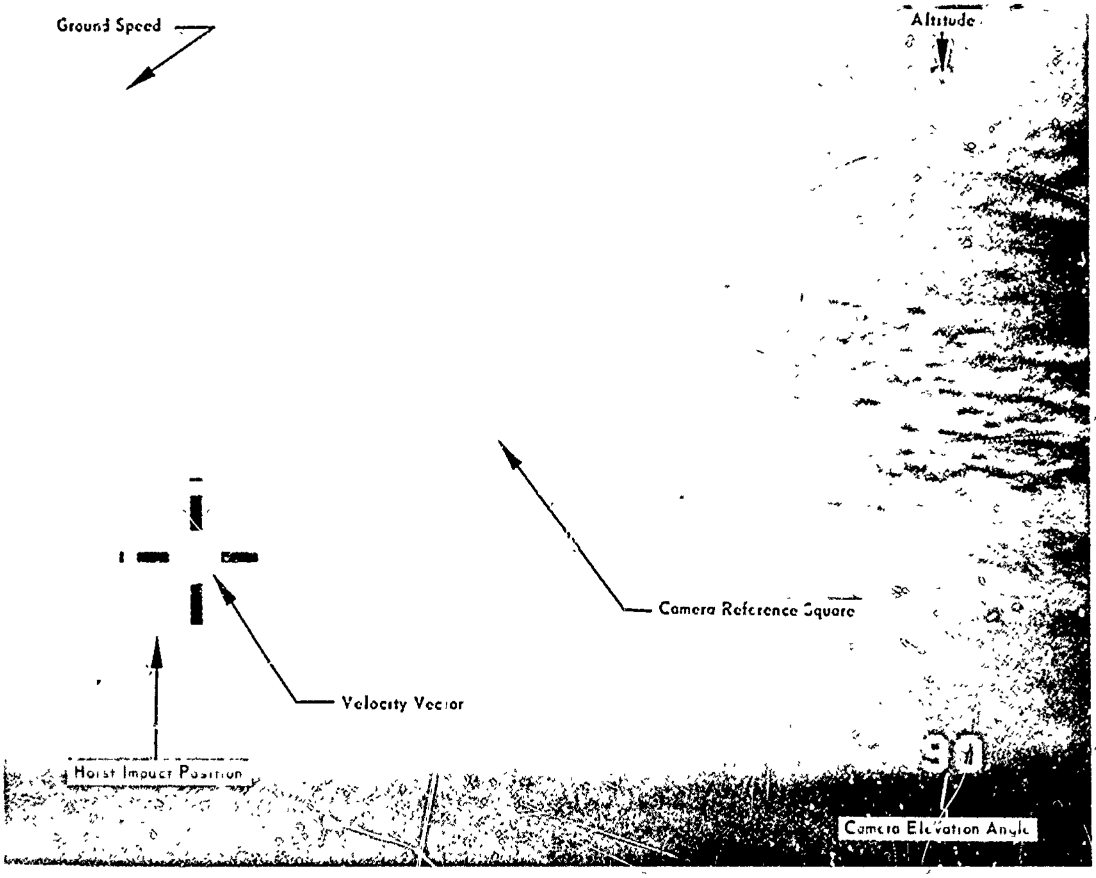


Figure 5 Low Light Level Television Display Hover Mode

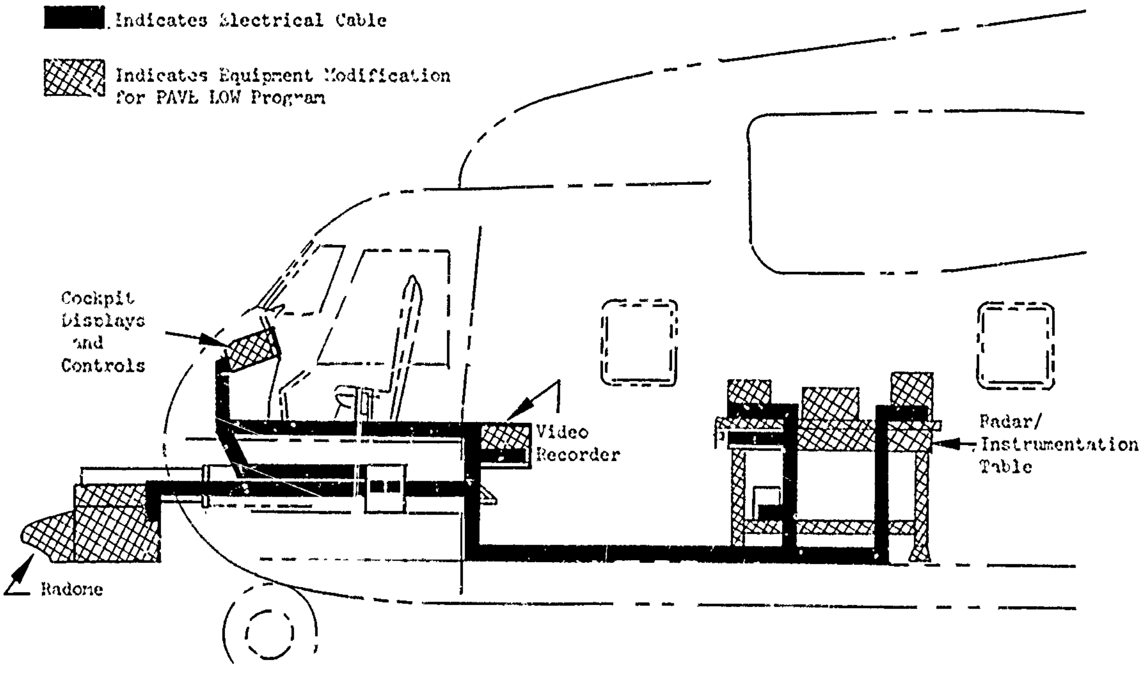


Figure 6 PAVE LOW Equipment Installation

Figure 7 AN/APQ-141 Radome Installation

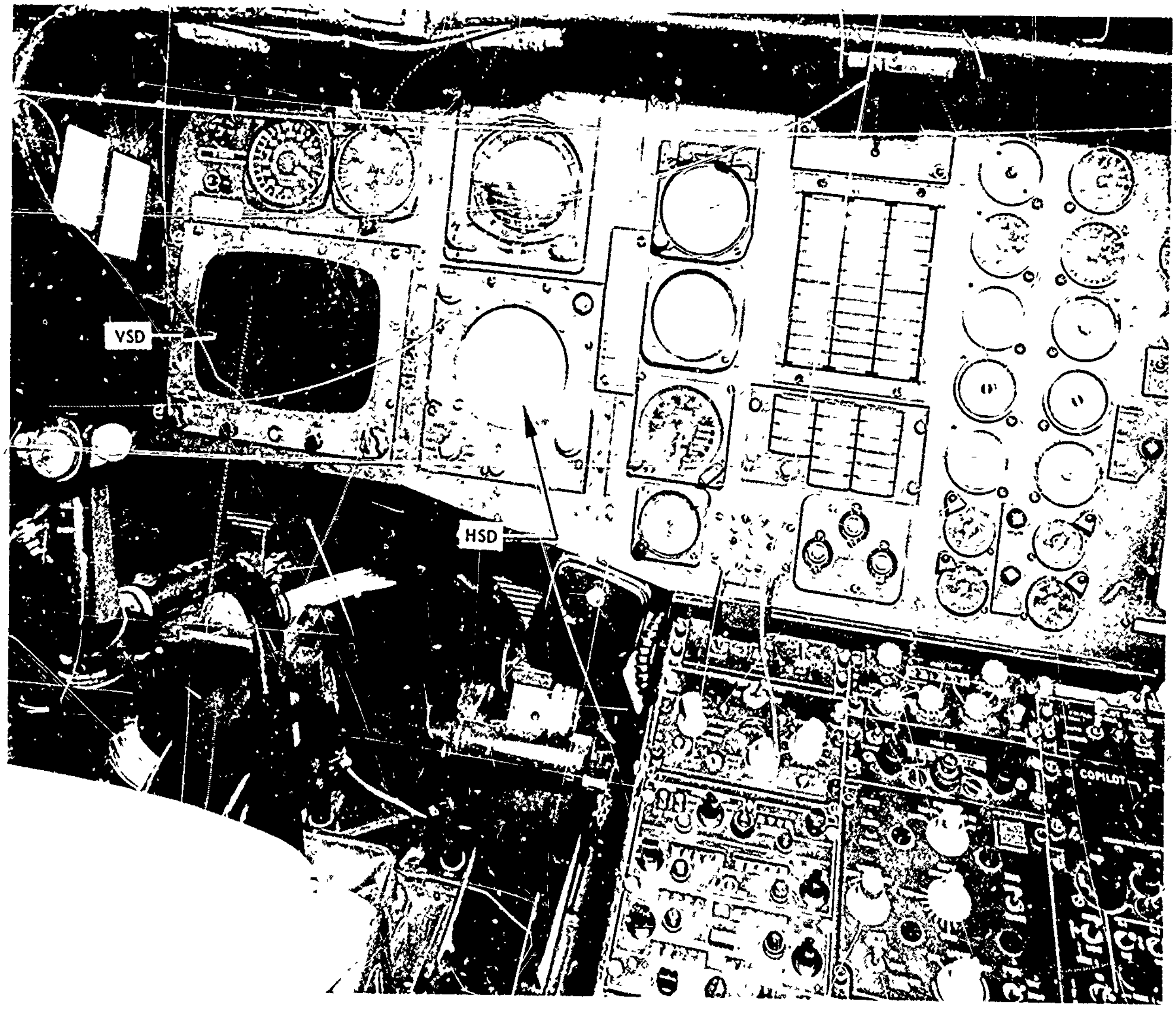


Figure 8 Copilot's Instrument Panel

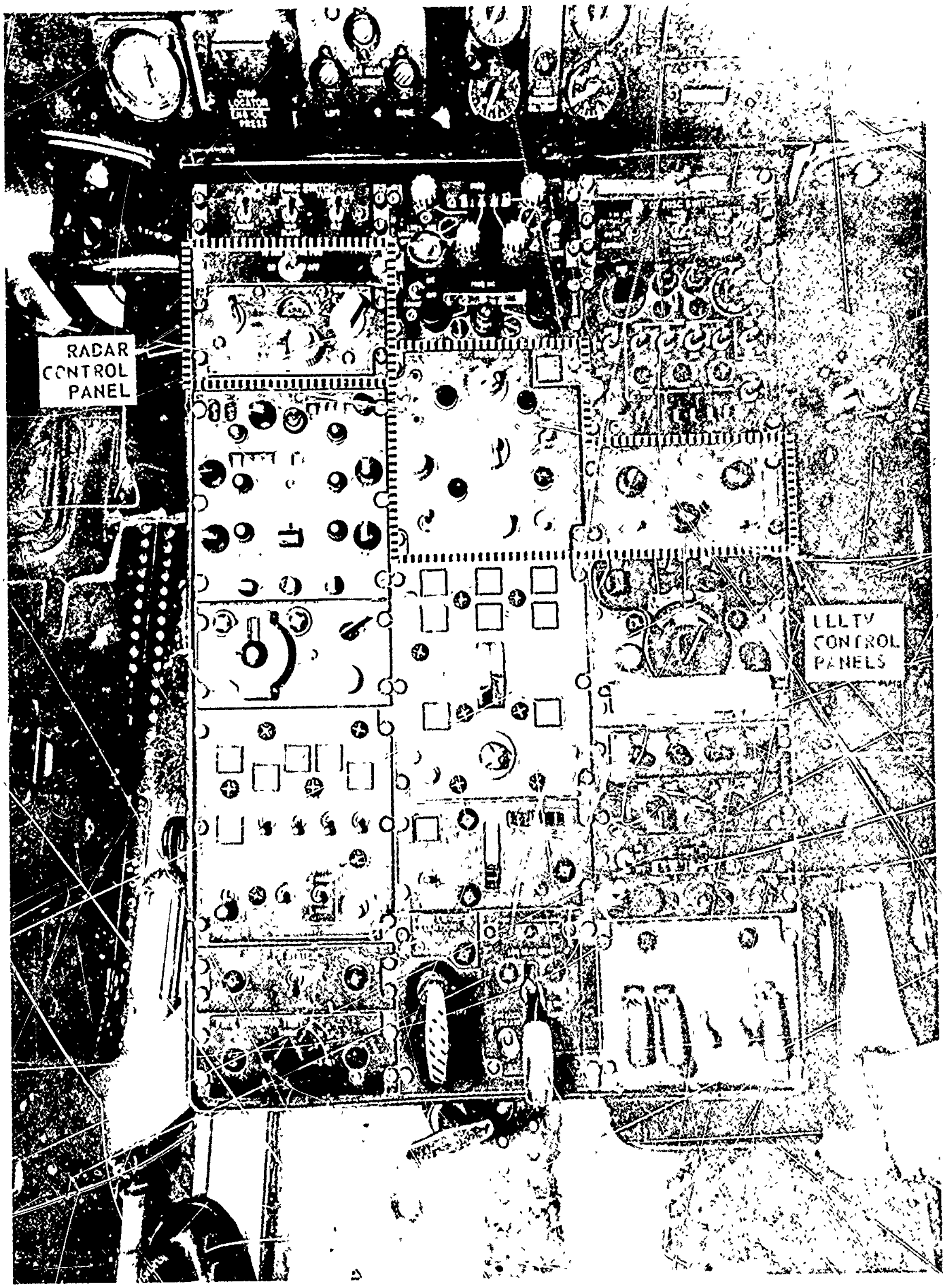


Figure 9. Cockpit Lower Center Console

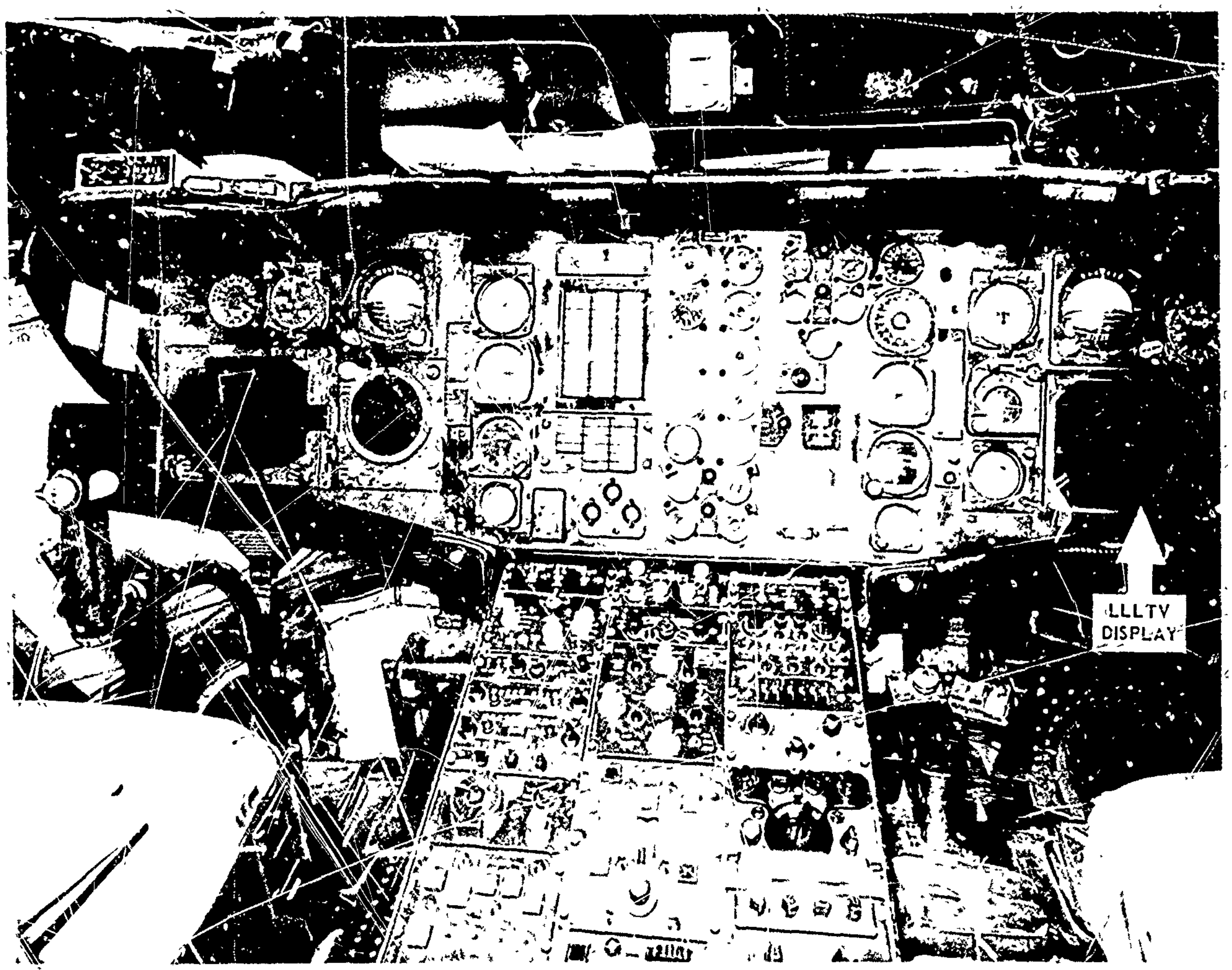
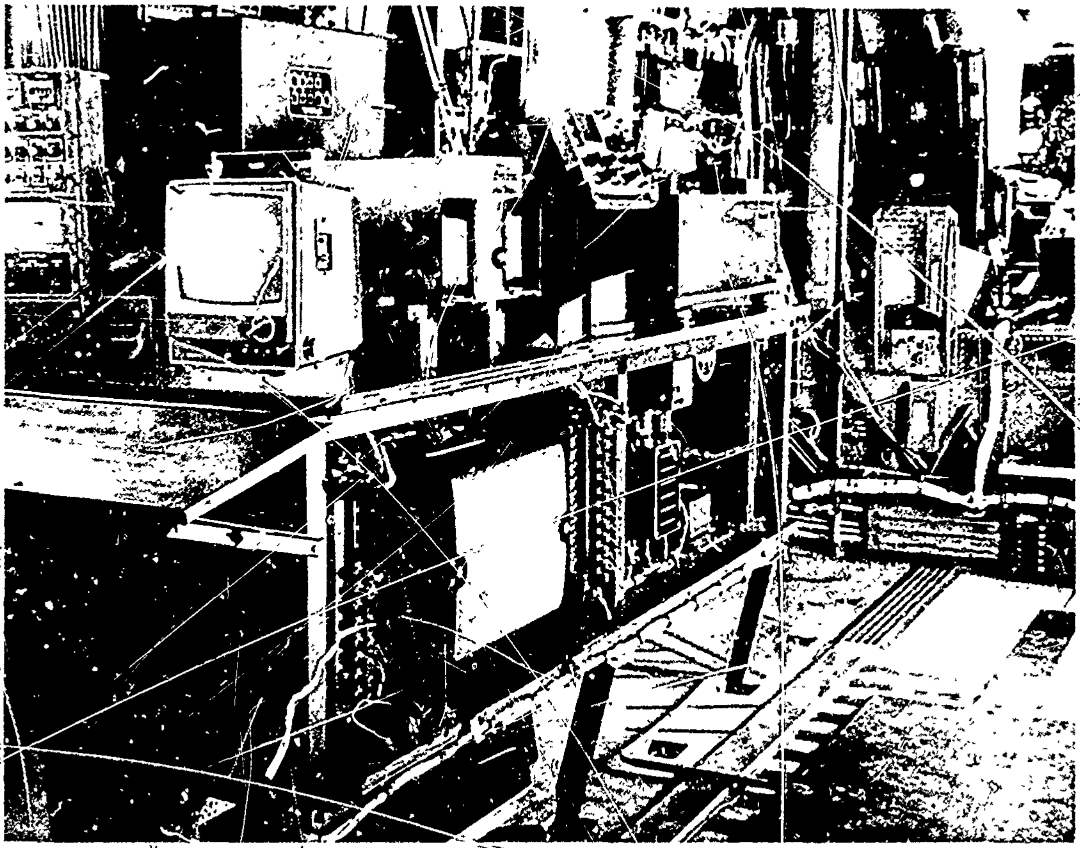


Figure 10 Pilot's Instrument Panel



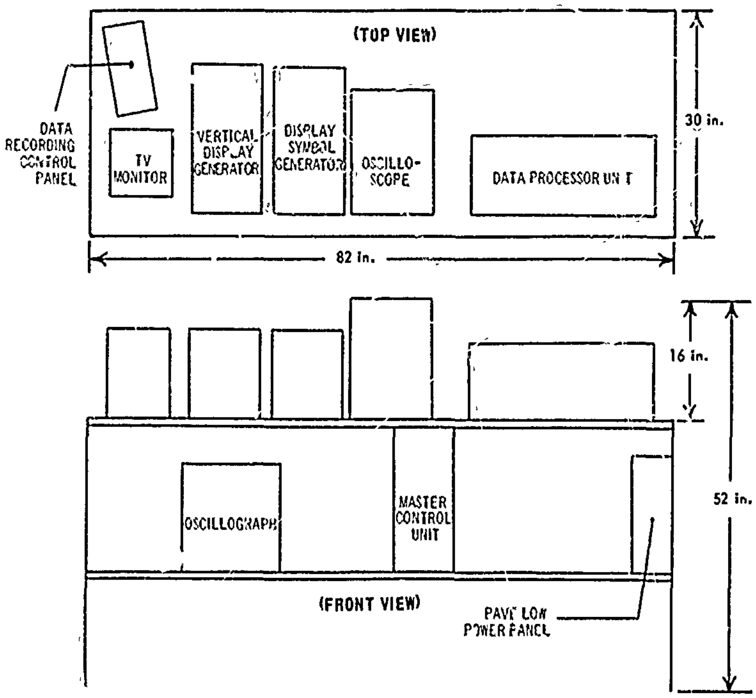


Figure 11 Instrumentation/Radar Table

TEST AND EVALUATION

The PAVE LOW test and evaluation project began after the completion of the required Class II modification on 28 April 1972. Problems were encountered with the TFRIS that eliminated some planned testing in remote areas. Doppler radar malfunctions were numerous and constituted a severe problem in the test program, causing many delays. As a result of these delays and time constraints on the program, development efforts were terminated on 31 October 1972. The test program was required to be completed by 3 December 1972. As a result of the heavily compressed testing schedules and the limited TFR system development, many of the originally planned tests had to be eliminated. These included overwater flights, flights over heavy vegetation and tall trees, and simulated rescue missions at night. Nevertheless, a sufficient number of test items were completed to provide an evaluation of the key performance parameters.

HORIZONTAL SITUATION DISPLAY

Ground Map Mode

The HSD provided a very good radar picture of the 90-degree quadrant in front of the aircraft. It was possible to tune the picture to distinguish between individual buildings and runways at Edwards AFB and Mojave airport. The target definition was rated as satisfactory and the display was very usable for radar navigation purposes.

The HSD had four control knobs located on the indicator unit and the radar control panel contained two more, all of which affected the quality of the presentation. Extensive retuning of each of these controls was required every time a different range was selected. This created an objectionably high pilot workload. The excessive attention required in order to obtain a usable presentation on the HSD seriously detracted from the ability of the pilot to safely accomplish the terrain following task. Future HSD's should be designed to minimize the control adjustments necessary to maintain a good quality presentation, especially when changing ranges. **(R 26)**[1]

The brightness control was extremely sensitive, which made proper adjustment difficult under optimum conditions. In light turbulence, proper adjustment required the full attention of the pilot. The brightness control knob also controlled the intensity of the range marks and course line. At times the range marks and course line could not be seen unless the brightness was set so high that most of the details of the presentation were obscured. A separate control should be provided for the range marks and course line brilliance. The sensitivity of the brightness control should be reduced to a sensitivity more compatible with the environment of a helicopter. **(R 27, R 28)**

The HSD range select knob was also the ON-OFF switch. The display was inadvertently turned off several times when changing ranges. This was unsatisfactory because each time the display was turned off, there was a 5-minute delay for electronic circuit warm-up time before the dis-

[1] Boldface numerals preceded by an R correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

play could be used again. The range selection/ON-OFF knob should have a press or lift-to-turn feature to turn it off. (R 29)

The HSD required a high brightness level for many of its modes and at night the HSD was too bright. The HSD was not equipped with a filter for night operations. The test unit was fitted with a red filter from an F-4 gun sight that proved satisfactory. The production radar HSD should have a red filter for night operation. (R 30)

The HSD required a considerable tuning effort to display objects at the shorter ranges. Objects within one-half mile could not be displayed, even on the two-mile range. Since the LNRS mission included low level maneuvering within 3 miles of the survivor and terminated in a 200- to 500-foot hover within a quarter mile of the pickup site, terrain features within a half mile of the helicopter need to be displayed. The HSD should have the capability of displaying objects within a quarter mile of the helicopter on both the two-mile and five-mile displays. (R 31)

Terrain Clearance Mode

The clearance plane selected for the TC mode was a plane passing through the helicopter's longitudinal and lateral axes. In the TC mode, the HSD displayed all terrain that was higher than that plane. Terrain at the same height as the helicopter was not always displayed, so at times the helicopter was less than 10 feet above the surface although the HSD indicated terrain clearance. This was compounded by the inability of the HSD to display objects closer than one-half mile. The TC mode should be provided with a clearance plane offset at least 200 feet below the aircraft. (R 24)

The TC mode did not provide usable information in turns. The HSD displayed everything above the clearance plane through the center of the aircraft. Thus, as the helicopter banked, the HSD showed solid terrain on the side of the scope in the direction of the turn, and nothing on the other side. Lack of TC information during a turn greatly reduced the effectiveness of this mode of operation and antenna stabilization should be provided in a production model radar system. (R 25)

VERTICAL SITUATION DISPLAY

Terrain Avoidance Operation

The VSD and the HSD together provided a good picture of the terrain in the 90-degree quadrant forward of the helicopter. The HSD in the GM mode provided a map-like display of the terrain ahead which allowed the pilot to navigate the most desirable route through the area. The VSD showed the vertical contours with command steering to clear large obstacles directly in front of the aircraft. The display of vertical contours allowed the pilot to fly through saddles and valleys for maximum concealment.

The TA mode of operation was also used in conjunction with the LNRS. During LNRS approaches to an area, the radar allowed the pilot to navigate and turn in valleys Final approaches were flown past hills, to areas between two hills, and to the base of hills. The radar provided the pilot with accurate helicopter-to-hill range information and the contours of the terrain ahead. This information, used with the LLLTV display, allowed

low speed maneuvering (less than 30 knots) in valleys and around hills during the LNRS final approach. Doppler navigation was used to direct the helicopter to the desired location. The displays also were an aid in determining the most expeditious route for departure from the pickup site. Use of the TF/TA radar greatly increased the capability of the LNRS.

The VSD picture became unusable at altitudes over 3,000 feet above ground level (AGL). At altitudes above 1,500 feet, portions of the contour lines pulled down to the bottom of the display. This condition was called "spiking". The amount of spiking increased as altitude increased until the display was useless with no contour lines visible above 3,000 feet AGL. The VSD should provide a valid display at all altitudes. (R 20)

The vertical scale of the VSD was unsatisfactory in the TA/TF mode of operation. The hills displayed on the 2.5- and 5-mile range lines of the VSD did not appear large enough. Hills 1,300 to 1,500 feet above the surrounding terrain were barely discernable at 5 miles and appeared smaller than the visual size of the hill at 2.5 miles. Saddles easily seen visually could not be detected until within one mile. The vertical scale of the VSD should provide better definition of hills at the 2.5- and 5-mile ranges. (R 22)

Terrain Following Operation

The VSD generally provided a very suitable display for a manual terrain following system. The display was uncluttered and required very little training to properly interpret the display. The contours displayed added a great deal to the pilot's confidence in the command steering. This type of display was excellent for the LNRS mission of the HH-53. However, there are several areas in which improvements could be made.

The vertical scale of the VSD was also unsatisfactory for manual terrain following. A climb of 6 degrees was indicated by a vertical displacement of only 0.54 inches. The command box was 0.5 inches square or approximately 5 degrees from top to bottom. Thus the pilot could fly with the cross in the box and vary the flight path as much as five degrees. As can be seen in figure 12, the pilot kept the velocity vector within 1 degree of the command vector only 57 percent of the time. However, the velocity vector was kept within 2 degrees of the command vector 86 percent of the time which indicates that the pilot could keep the velocity vector within 0.2 inches about 86 percent of the time. This implies that doubling the scale would allow the pilot to maintain the desired flight path more precisely. This indicates that an improvement can be made by increasing the vertical scale. The vertical scale should be improved to allow the pilot to more closely follow the flight path commanded. The solution to this problem should also be compatible with the vertical scale requirements of the TA operation previously noted. A combination of a larger linear scale for the first 10 degrees above the horizon and a reduced non-linear scale above 10 degrees would be one possible solution. A logarithmic scale would also be a possible solution. (R 23)

Another factor influencing the pilot's ability to follow the commanded profile was that the command steering symbol jumped vertically about the proper position, especially during the initiation of climb and descent commands. This vertical oscillation reduced the precision with which TF commands could be followed. The vertical oscillation was so

pronounced at the initiation of climb commands that a delay was encountered in establishing the climb. Since the command was so erratic at this point, small up commands were masked by the vertical oscillation and the pilot did not start a climb until a firm up command was displayed. This was generally about a three-degree climb which rapidly increased to six degrees. By the time the pilot realized that the display was commanding a climb instead of false vertical jumps, he was late in establishing a climb. Because of this delay, an abrupt entry into the climb was required and, because the airplane had not previously followed the command precisely, a larger climb angle had to be commanded. The vertical oscillation should be eliminated and a smooth command at the initiation of climbs and descents should be provided. (R 19)

MANUAL TERRAIN FOLLOWING

Terrain Following Radar Accuracy

The accuracy of the PAVE LOW TFR system was tested over four different terrain profiles. The terrain profiles were classed as smooth, a moderate hill, a rugged mountain, and a series of hills. Edwards TFR Route No. 2 provided the smooth terrain and the moderate hill. This route went through the Edwards instrumented range as shown in figure 13. Askania phototheodolite coverage was utilized to record a precise time history of aircraft position, altitude, velocity, climb rates, and velocity vector. The time histories thus obtained were compared with the onboard instrumentation data to establish confidence levels in the accuracy of the onboard instrumentation system. A brief discussion of the accuracies of the instrumentation systems is included in appendix IV. The rugged mountain terrain testing was done at Soledad mountain (figure 14). The series of hills used extended from Willow Springs to Soledad mountain as shown in figure 15. No radar or Askania coverage was available in the Willow Springs or Soledad Mountain area. Therefore, all data were obtained from onboard instrumentation only. All TFR accuracy tests were flown at a nominal ground speed of 120 knots, and the pilot attempted to keep the velocity vector centered within the command vector box at all times.

Performance Over Smooth Terrain

The first portion of Edwards TFR Route No. 2 was used to determine the TFR performance over smooth terrain. Radar vectors from precision X-band radar were used to keep the aircraft on course because of a lack of suitable landmarks in the desert terrain. Seven runs over smooth terrain were made at a commanded altitude of 200 feet, and two runs were made at a commanded altitude of 400 feet.

TFR performance over smooth terrain was generally rated as good. The pilot found it easy to fly manual terrain following over smooth terrain, and there were no large excursions of either the command vector or the velocity vector. Figure 16 shows parameters recorded on flight 43-1. This was considered a very typical flight over smooth terrain. Similar parameters for other flights over smooth terrain are shown in figures 1 to 9, appendix III.

Figure 17 is a histogram of altitudes on all 7 flights at 200 feet over the smooth terrain portion of Edwards TFR Route No. 2. The maximum altitude recorded was 255 feet and the minimum altitude was 175 feet.

Histograms of altitude versus time for the individual flights are included in appendix III. As can be seen on figure 18, the median altitude for all these flights was 208 feet, or just eight feet above the commanded altitude of 200 feet AGL. The TFR performance was consistent over smooth terrain as verified by the fact that the altitude was between 190 and 235 feet AGL 90 percent of the time. Only 5 percent of cases fell below 190 and less than 1 percent fell below 180 feet AGL.

Flights 48-1 and 48-2 were flown over the same portion of the Edwards TFR course as those above except that these two flights were at a commanded altitude of 400 feet AGL. Histograms of altitude versus time over smooth terrain for these two flights are included in appendix III. Figure 19 portrays the cumulative distribution of altitude versus time for these two runs. The median altitude was 387 feet with 90 percent of all cases falling between 360 and 410 feet. Eighty-two percent of all cases were below the commanded altitude of 400 feet.

Manual terrain following at a commanded altitude of 400 feet over smooth terrain was barely satisfactory in that the median altitude was 13 feet below the commanded altitude and the aircraft was below the commanded altitude over 80 percent of the time. In a production system, the median altitude over smooth terrain should not be lower than the commanded altitude. **(R 12)**

Performance Over a Moderate Hill

The last portion of the Edwards TFR Route No. 2 went over Haystack Butte, an isolated butte with a vertical rise of 400 feet and a slope of about 20 degrees. This was considered a moderate hill for TFR evaluation purposes. Seven runs were made at a commanded altitude of 200 feet AGL and data from these individual runs are shown on figures 3 through 9, appendix III. Flights 48-1 and 48-2 were flown at a commanded altitude of 400 feet AGL. The manual TFR system performance over a moderate hill was unsatisfactory in that the altitude at the crest was too low and descent behind the hill was not rapid enough.

Figure 20 shows the parameters recorded on flight 48-3 over Haystack Butte. This flight was at a commanded altitude of 200 feet AGL and was considered typical of all runs over Haystack Butte including those at 400 feet AGL commanded altitude. Also included on figure 20 is a computer-predicted flight profile supplied by Norden division of United Aircraft. The first thing to be noted in comparing the actual profile and the predicted profile is that the aircraft started its climb late. The aircraft was not established on a 6-degree climb until 1,100 feet (approximately 5 1/2 seconds) past the point at which the climb should have started. This was caused by the command vector not commanding a six-degree climb at the proper distance from the hill. The computer predicted command started to indicate a climb at 5,400 feet before the crest, and the actual command vector did not indicate a climb until 4,400 feet before the crest, which is 1,000 feet or 5 seconds late. From an average of 7 runs at 200 feet AGL over the same course, the point at which the command vector initiated a steady climb command was 4,300 feet prior to the crest, which was 5.5 seconds later than predicted. It can also be noted in figure 20 that the command vector did not reach a positive 5 degrees until 800 feet past the Norden prediction, about 4 seconds late. The average from the same 7 runs indicates that a plus 5-degree command was not reached until 2,150 feet prior to the crest. This is 6.0 seconds past

the point at which the predicted command indicated a 5-degree climb. Performance of the command vector was unsatisfactory in that the climb command occurred late.

As a result of the climb command occurring late, it was often necessary to exceed the desired six degree climb. Table II presents a summary of the flights over Haystack Butte. On the flights with a commanded altitude of 200 feet AGL, the average maximum climb command was 8.17 degrees at an average distance of 1,600 feet prior to the crest. The maximum climb command experienced was 9.64 degrees and the smallest of the maximum climb commands for any one run was 7.5 degrees. The climb command was unsatisfactory because the desired maximum climb command of 6 degrees was consistently exceeded.

Table II

SUMMARY OF FLIGHTS OVER HAYSTACK BUTTE

Flt No.	Altitude at Crest (ft AGL)	Command Vector at Crest (deg)	Velocity Vector at Crest (deg)	Max Climb Command		Time[1] of First Down Command (deg)	Command Altitude (ft AGL)
				Time[1] (sec)	Command (deg)		
48-3	154	+3.35	+6.27	-6.9	+8.84	+5.[illegible]	200
48-4	154	+1.61	+4.36	-15.4	+8.30	+4.4	200
49-1	190	+3.88	+8.15	-6.0	+8.30	+3.0	200
49-2	177	+3.75	+8.15	-6.0	+9.64	+1.0	200
67-1	169	+1.34	+4.05	-7.0	+7.50	+1.0	200
67-2	15[illegible]	+2.28	+4.73	-7.0	+7.90	+1.0	200
67-7	173	+1.21	+4.05	-9.0	+6.70	+2.0	200
Avg[2]	167	+2.49	+5.68	-8.2	+8.17	+2.7	200
48-1	277	+1.87	+3.95	-4.1	+9.24	+6.1	400
48-2	361	+3.48	+6.55	-6.9	+7.77	+5.4	400
Avg[3]	319	+[illegible].67	+5.30	-5.5	+8.5	+5.7	400

Notes:

[1]Time is given in relation to transiting the crest. Positive values indicate seconds after transiting the crest.

[2]Avg - This row is the average value computed from all flights at a command altitude of 200 feet AGL.

[3]Avg - This row is the average value of flights at a command altitude of 400 feet AGL.

The predicted climb angle was 6 degrees, which would allow operation at 13,000 feet density altitude at 40,000 pounds gross weight. An 8-degree climb angle reduces the maximum density altitude to 11,000 feet at 40,000 pounds. However, at lower altitudes and weight the maximum capabilities of the HH-53B were not realized. The TF profile resulted in the helicopter being well above the commanded altitude for long distances while climbing toward hills. Further investigation of TF profiles should be made to select the optimum TF profile for the LNRS mission. A pilot selection of a template for either a 6-degree or an optimum performance climb rate

should be provided to better utilize aircraft performance capabilities. (R 14), R 15)

Referring to table II, the average altitude at the crest of Haystack Butte was 167 feet AGL when a commanded altitude of 200 feet was selected. The maximum crest altitude was 190 feet and the minimum was 151 feet. This was unsatisfactory and also unsafe for actual night operations. A production TFR system should be capable of consistently maintaining the commanded altitude at no less than 90 percent of the commanded value and no more than 120 percent of the commanded altitude when transiting crests. (R 1)

Figure 20 shows that on flight 48-3 the actual aircraft altitude above ground level was below the altitude predicted for the climbing portion of the flight. Table II shows that the command vector average of 7 flights was +2.5 degrees at the crest which corresponds to a 525 foot-per-minute (fpm) rate of climb. The minimum command vector at the crest was 1.21 degrees and the maximum was 3.88 degrees. The first descent command did not occur until an average of 2.7 seconds past the crest. Since an aircraft is inherently equally susceptible to ground fire or radar detection on both the front and rear side of a hill, a good terrain following system should provide a symmetrical altitude profile over a hill. This implies a zero command and velocity vector at the peak to reduce the ballooning over the back side of the hill. The average of the velocity vectors at the crest on the 200-foot commanded clearance runs against Haystack was 5.68 degrees or a climb rate greater than 1,100 fpm. Table II also shows very similar results for terrain following runs at 400 feet commanded clearance. The previous comments about the 200-foot commanded clearance runs apply as well to the 400-foot flights. The terrain following computer mechanization should be modified so that the command vector does not exceed a positive one-degree climb when transiting the peak. (R 17)

Figure 20 shows a descent rate of 3 degrees commanded when past the hill even though the height above ground level was over 600 feet and there were no obstacles in front of the aircraft. The commanded rate of descent was about 625 fpm. This was unsatisfactory as the aircraft remained above the commanded altitude for too long a period of time. During the early phase of the program a commanded rate of descent of 1,500 to 1,800 fpm was provided, but was changed in an attempt to increase the altitude over hill crests. The higher rate of descent (1,500 to 1,800 fpm) returned the helicopter to the commanded altitude rapidly, yet the rate of descent was not high enough to cause pilot apprehension. A smooth reduction in rate of descent was commanded as the aircraft neared the desired altitude, providing a smooth transition, to the commanded altitude. The commanded rate of descent for a production TF/TA radar should be 1,500 to 1,800 fpm until the aircraft is within 300 feet of the set clearance altitude and then reduced to about 1,000 fpm maximum. This should provide a quick descent and not produce a highly undesirable undershoot of set terrain clearance altitude. (R 2)

Performance Over a Rugged Mountain

The Soledad Mountain TFR course was used for these tests (figure 14). The aircraft was maintained on course by flying precisely over each of five identified check points and keeping the course strobe on the HSD lined up with the crest of the mountain. Soledad Mountain had a vertical rise

of 1,270 feet within a horizontal distance of 4,150 feet. The average slope was 17 degrees. Eight flights at 200 feet AGL and 4 flights at 400 feet AGL were flown over this course during the test. Data from these individual runs are shown in figures 10 through 21, appendix III. Table III presents a summary of some of the key points on all 12 flights as well as the average of these results.

The performance of the PAVE LOW manual TFR system was unsatisfactory over a rugged mountain. The two most significant problems were that the clearance altitude at the crest of the mountain was less than the commanded altitude and the climb commands generated exceeded the desired 6-degree maximum. Table III shows that in no case was the commanded altitude exceeded at the crest of the hill. Figure 21 portrays a profile of a typical flight (flight No. 48-7) compared with a computer predicted profile. The Norden predicted command began to rise at approximately 14,000 feet prior to the peak. In most tests, as in flight 48-7, the actual command also began to rise at approximately the same distance from the peak. However, a significant difference was that where the predicted command rose rapidly to indicate more than a 6-degree climb at 11,500 feet prior to the peak, the actual command did not reach 6 degrees until the aircraft was approximately 3,000 closer to the peak. This caused the aircraft to be in a position below the predicted profile very shortly after the climb started. This was true on flights at 400 feet AGL as well as flights at 200 feet AGL.

Table III

SUMMARY OF FLIGHTS OVER SOLEDAD MOUNTAIN

Flt No.	Altitude at Crest (ft AGL)	Command Vector at Crest (deg)	Velocity Vector at Crest (deg)	Maximum Climb Command		Time[1] of First Down Command (deg)	Command Altitude (ft AGL)
				Time[1] (sec)	Command (deg)		
48-7	157	+1.20	+3.80	-35.5	+9.10	+1.0	200
48-8	156	+2.40	+5.50	-31.9	+9.40	+1.9	200
54-1	188	+2.25	+5.27	-31.0	+8.22	+5.0	400
54-2	163	+0.27	+2.84	-28.6	+9.42	+0.4	400
59-3	[illegible]	-1.23	+1.64	-14.0	+6.42	-4.0	200
59-4	200	-0.41	+2.05	-33.0	+9.56	-1.0	200
69-1	173	-0.43	+1.89	-27.0	+8.25	0.0	200
70-1	199	+2.28	+4.77	-35.0	+10.31	-2.0	200
Avg[2]	176	+0.79	+3.47	-29.5	+8.85	0.0	200
48-5	389	+0.80	+3.82	-34.5	+8.04	+3.2	400
48-6	320	-0.94	+1.64	-26.2	+8.30	+0.7	400
59-1	294	-0.41	+2.18	-19.0	+6.69	-4.0	400
59-2	331	-0.19	+2.73	-42.0	+9.56	-1.0	400
Avg[3]	334	-0.19	+2.59	-30.4	+8.15	-0.3	400

Notes:

[1]Time is given in relation to transiting the crest. Positive values indicate seconds after transiting the crest.

[2]Avg - This row is the average value computed from all flights at a command altitude of 200 feet AGL.

[3]Avg - This row is the average value of flights at a command altitude of 400 feet AGL.

It can also be noted on flight 48-7, that beginning at approximately 9,000 feet prior to the peak, the velocity vector tended to remain slightly less than the actual command until approximately 7,000 feet prior to the peak. As in the test flights over Haystack Butte, this is also attributed to the command vector symbol jumping vertically. The pilot attributed the sudden rise of the command symbol to be a spurious jump in the command. When he later (approximately eight seconds) realized that it was not a spurious command, the aircraft was further below the desired profile. This also occurred on flights at 400 feet AGL and can be noticed in the individual flight parameters in appendix III.

At a point prior to the crest, generally around 3,000 feet, the pilot would begin to fly the aircraft on the high side of the command vector. As indicated in table III, the velocity vector was still significantly above the command vector when transiting the crest. When interpreting the histograms of the velocity vector minus the command vector, care must be exercised to avoid misinterpretation. The areas on the left side of the histogram were increased because of misinterpretation of or inability to follow the command vector. The areas on the right side of the histogram were increased because of a desire to keep the velocity vector above the command vector. The same reasoning applies to figure 22. It can be noted in figure 22 that the velocity vector was maintained within 1 degree of the command vector approximately 60 percent of the time. This compares very favorably with the 57 percent recorded in figure 12.

It was evident that the manual TFR system required a good deal of close attention and concentration by the pilot. Inattention for even short periods of time could be critically dangerous. If a pilot's attention were occupied elsewhere for even as little as 10 seconds, the aircraft could become too close to an obstacle to climb over it with the desired clearance. An audible warning signal should be provided whenever a climb beyond the specified aircraft performance is necessary. The added confidence from the knowledge of an audible warning system should also help alleviate pilot fatigue on longer missions. (R 13)

Performance Over a Series of Hills

Five flights were made over the TFR course at Willow Springs shown in figure 15. Table IV presents a summary of the results obtained over this course. It can be seen in table IV that again the altitude at the crest of the hills was lower than desired on all flights. Because of the malfunctioning of a portion of the instrumentation system, an accurate plot of the aircraft flight path over the entire course could not be obtained. The plots shown in figures 22 through 27, appendix III, are therefore only general representations of the flight paths involved. However, the plots of the command vector and velocity vector, are accurate and point out that the descent rate did not exceed three degrees. As a result the aircraft did not descend to 200 feet AGL between peaks. The transition from climbing flight to descending flight and vice-versa was smooth but the slow descent rate did not allow the aircraft to follow the terrain profile as closely as desired.

Pilot and Aircraft Response

A limited investigation of aircraft/pilot response time was performed with three AFFTC pilots and two MAC (ARRS) line pilots. A test switch

Table IV

SUMMARY OF FLIGHTS OVER WILLOW SPRINGS ROUTE

Flight No.	Crest No.	Altitude at Crest (ft AGL)	Command Vector at Crest (deg)	Velocity Vector at Crest (deg)	Maximum Position Command		Time of First Negative Command (sec)	Set Clearance Altitude (ft AGL)
					Time[1] (sec)	Command (deg)		
69	1	166	-1.99	+0.27	-38.0	6.97	-6.0	200
	2	220	-2.28	-0.68	-17.0	5.83	-3.0	200
	3	198	-2.70	-4.73	- - -	- - -	- - -	200
	4	220	+4.69	+5.13	-19.0	6.54	- - -	200
	5	166	-3.27	-0.95	-20.0	8.96	-9.0	200
72	1	177	-1.60	+0.28	-30.0	6.82	-4.0	200
	2	189	-1.45	+0.96	-23.0	2.47	-10.0	200
	3	215	-2.32	-1.93	- - -	- - -	- - -	200
	4	233	+4.21	+3.99	-15.0	5.66	- - -	200
	5	110	-2.47	- - -	-38.0	6.24	-5.0	200
72	1	145	-2.18	-1.38	-34.0	9.58	-6.0	200
	2	142	-1.02	+1.10	-19.0	6.10	-4.0	200
	3	161	-2.76	-1.79	- - -	- - -	- - -	200
	4	338	+3.78	+3.72	-19.0	6.10	- - -	200
	5	82	-1.74	+0.55	-24.0	6.10	-5.0	200
70	1	168	-1.87	+0.27	-36.0	8.44	-5.0	200
	2	139	-0.54	-0.95	-12.0	3.48	-4.0	200
	3	130	-2.28	-1.91	- - -	- - -	- - -	200
	4	211	+5.09	+6.55	-20.0	6.03	- - -	200
	5	171	-0.13	+2.59	-33.0	6.96	-1.0	200
61	1	356	-2.30	-0.81	-11.0	6.90	-3.0	400
	2	353	-0.27	+2.30	-20.0	5.54	-1.0	400
	3	390	-2.43	-0.81	- - -	- - -	- - -	400
	4	509	+4.60	+6.29	-12.0	7.03	- - -	400
	5	287	-0.54	+2.43	-22.0	6.76	-3.0	400
69	1	185	-0.43	+1.62	-33.0	8.25	0	200
	2	157	+0.28	+2.43	-18.0	4.12	0	200
	3	169	-2.28	-1.89	- - -	- - -	- - -	200
	4	195	+5.69	+4.59	-17.0	7.40	- - -	200
	5	182	+2.28	+5.40	-7.0	7.68	+5.0	200

[1] Time is given in relation to transiting the crest. Positive values indicate seconds after transiting the crest.

was installed on the radar power panel junction box located in the aircraft cargo area. It allowed the Command Steering Vector Symbol to indicate +6°, 0°, or -6° as viewed on the VSD. The signal for these indications was generated directly to the VSD through a precision voltage divider.

Individual test intervals were initiated with the aircraft either stabilized in level flight or at a constant descent or ascent, for example, a commanded change from a 6-degree stabilized descent to a level flight command. Each test was initiated by positioning the switch to the desired command steering situation, concurrently "eventing" the instrumentation data and recording time. Each test was terminated and time recorded when the pilot had positioned the aircraft velocity vector within the command vector symbol as viewed on the VSD.

The 13 individual response time intervals recorded are depicted graphically in appendix III, figures 28 through 40 and summarized in table 1.

The aircraft/pilot responses recorded during these tests represent only limited sampling and tests were not under controlled conditions of gross weight, center of gravity, density altitude, etc. Therefore, these results should not be generalized as a true and accurate measure of response times. The results, however, do infer the general shapes of aircraft/pilot response to a step function input command.

Table I indicates response time averages of the five pilots for six separate commanded maneuvers. In the instance of the step function input command for a change of flight vector from a 6-degree climb to horizontal flight, the response times averaged 5.7 seconds which implies a distance traveled of approximately 1,100 feet. A trend of some significance is noted in comparing response times for commanded "pushover" type maneuvers with commanded "pull-up" maneuvers. The "pushover" response was 1 to 2.5 seconds longer, allowing 200 to 500 feet additional forward travel during the "pushover" maneuver. Analysis of figures 28 through 40, appendix III, reveals that the response to step command change from 0 to +6 degrees is very closely approximated by a pure delay of 1 second and a ramp function response. The same response can be seen to a command input change from 0 to -6 degrees. Figure 24 shows how closely the above response fits the 13 sample cases. It can be seen that the pilot/aircraft combination has acted as an integrator and become part of an adaptive control system to smooth out any sudden changes in command. The question can then be raised as to whether it is better to have the computer command mechanization smooth out the command, or present sharper commands and let the pilot/aircraft response be the adaptive control for a smoothed maneuver. While command smoothing is mandatory for an automatic control system, it need not be for a manual system with a pilot acting as an adaptive control. With more smoothing of the command performed by the computer, the average height above the terrain will be higher. However, the presentation of step function commands is not desired by most pilots and would probably increase tension and fatigue. In the PAVE LOW command mechanization, decreasing the amount of computer smoothing applied to commands might serve to improve the terrain following profile. The Norden computer mechanization of the TF command tends to inhibit the presentation of a step type command to the pilot. This is done as a safety factor for terrain clearance and also serves to limit the normal acceleration on the aircraft. However at the same time, this causes the aircraft to deviate more from an ideal TF profile to a slightly higher profile. Further investigation of response times and computer command mechanization is warranted as this could lead to reduction of the ballooning effect on the back side of a hill. (R 18)

Performance at Variable Speeds

The TFR template used in the PAVE LOW system was designed for a nominal ground speed of 120 knots. The tests were to investigate the effect of flying at speeds of other than nominal on the TFR performance. A series of runs over the Haystack Butte TFR course were flown for this purpose. The first and last runs were flown at a nominal ground speed of 120 knots to verify that the system was operating in a normal manner. The second and third runs were made at a nominal ground speed of 80 knots and the fourth and fifth runs were made at a nominal ground speed of 150 knots. In all other respects the tests were conducted in the same manner as previous TFR accuracy tests. Table V presents a summary of these test results and the average data from table II for comparison purposes.

Table V

VARIABLE SPEED PERFORMANCE
(200 Feet AGL)

Flt No.	Altitude at Crest (ft AGL)	Command Vector at Crest (deg)	Velocity Vector at Crest (deg)	Maximum Climb Command Time[1] (sec)	Maximum Climb Command Command (deg)	Time[1] of First Down Command (deg)	Ground Speed (kt)
67-3	149	+3.21	+6.1	-7.0	+8.84	+4.0	150
67-4	184	+3.75	+7.3	-7.0	+8.84	+3.0	150
67-5	100	-0.54	+1.6	-14.0	+6.2	-4.0	80
67-6	102	-0.54	+0.4	-15.0	+5.4	-3.0	80
Avg[2] at 120 kt	167	2.49	5.7	-8.2	+8.17	+2.7	120

Notes:

[1]Time is given in relation to transiting the crest. Positive values indicate seconds after transiting the crest.

[2]Avg - This row is the average value computed from seven flights at a commanded altitude of 200 feet and 120 knots ground speed.

Flight 67-3 and 67-4 were flown at 150 knots and the performance at this speed was not significantly different than the performance at 120 knots. Figures 41 and 42, appendix III, portray the parameters recorded in these two flights. The performance over smooth terrain was satisfactory at 150 knots with the median altitude being 200 feet AGL. The minimum altitude over smooth terrain was 175 feet and the maximum altitude was 230 feet. Figure 25 shows that 84 percent of the time, the recorded altitude over smooth terrain at 150 knots was within 90 to 110 percent of the commanded altitude.

Flight 67-5 and 67-6 were flown at 80 knots and show a significantly degraded performance from that at 120 knots. Referring to figure 25 it can be seen that the actual altitudes recorded over smooth terrain were significantly less than the desired 200 feet AGL. The minimum altitude was 138 feet, and the maximum altitude was 230 feet. The median altitude was 175 feet and 86 percent of all cases were below the desired altitude. In evaluating the performance at 80 knots over a moderate hill, table V

shows that this area of performance is also significantly degraded from that of 120 knots. The altitude at the crest of the hill was only 100 feet instead of the desired 200 feet. Figures 43 and 44, appendix III, show further degradation in performance in that the altitude over the second crest on Haystack Butte was even lower than 100 feet on both flights and on flight 67-5 was as low as 30 feet. The command vector had been indicating a descent for the last 2,500 feet or 18 seconds previous to the second crest even though the altitude was already low during this time. The command vector began to indicate a climb at the desired distances from the mountain, however it did not command a steep enough climb. The command vector indicated a full 6-degree climb 200 feet (or 6 seconds) later than it should have. As a result, the aircraft profile was below that desired when the pushover command was initiated. This resulted in the aircraft descending from an altitude that was already too low. The performance at a low groundspeed of 80 knots was unsatisfactory and TF operation at this speed would be hazardous. This would greatly reduce the effectiveness of the TFR system when departing a hover situation, to begin an egress route. A ground speed above 100 knots would have to be achieved prior to following the TFR commands. The TFR system should be provided with some means of operating at a variety of speeds both higher and lower than 120 knots. (R 10)

Descent to Terrain-Following Flight

For these tests, the TFR course northwest of Soledad Mountain was used. The aircraft was established at a groundspeed of 120 knots in level flight at altitudes of 600 and 1,300 feet AGL over a portion of the course where previous TFR testing indicated an altitude of 200 feet AGL would have been maintained. The TFR mode was selected for terrain following at 200 feet and the pilot followed the commanded descent and climb rates. Table VI presents a summary of these three tests.

Figures 45 through 47, appendix III, present profiles of the terrain clearance, command vector, and velocity vector for these flights. In all three tests, the TFR system provided a smooth transition from descent through level flight to climbing flight. The descent rate was too slow in all three cases; however, as a descent rate of more than 1,200 fpm would have been desirable.

Table VI

DESCENT TO TF FLIGHT

Descent No.	Initial Altitude (ft AGL)	Rate of Descent at 1,000 ft AGL (ft/min)	Initial Descent Rate (ft/min)	Altitude at Crest (ft AGL)	Maximum Climb Command (deg)
1	600	---	275	162	10.5
2	1,300	480	550	168	7.7
3	1,200	420	550	169	6.2

Performance Over Isolated Towers and Transmission Lines

On flight 70, TFR performance against an isolated radio tower was briefly investigated. Hawes Tower, a 1,226 feet AGL radio tower, located at 34°66' N. latitude and 117°22' W. longitude was used for this purpose. Several approaches were made at the tower with a 200-foot set clearance altitude and the TFR mode selected. The tower was easily located on the HSD in the GM mode. The track strobe on the HSD was used to insure that the TFR course was directly in line with the tower. The tower was not visible on the VSD, and no climb command was noted. The terrain following system would not have provided clearance over this obstacle.

Numerous passes over power transmission lines were made throughout the test program. The tall metal towers were displayed on the HSD as a series of dots forming a very distinctive pattern. Several passes were made directly at a specific tower. The direction of the pass was perpendicular to the direction of the transmission lines. The HSD course line and visual cues were both used for steering. There was no presentation of the towers on the VSD at any range, and no fly-up commands were noted. The radar altimeter showed a momentary altitude decrease as the tower was crossed and indicated the transmission lines were approximately 60 feet high. This agreed with a visual estimate of their height. The TFR system did not provide the proper clearance over transmission lines or isolated towers.

Performance Over Various Types of Terrain

Due to the desert location of Edwards AFB and the limited time available for the AFFTC evaluation, tests were not conducted over water, heavily vegetated areas, or snow-covered areas. The terrain used in the testing was classed as desert and bare mountain peaks. One flight (No. 70) was flown for the purpose of evaluating performance over sand dunes. The sand dunes were located at 34°56' N. latitude and 115°43' W. longitude and had a rise of approximately 700 feet over the surrounding terrain. Several passes at a commanded altitude of 200 feet were made toward this large sand dune. The dune was displayed on the VSD at approximately five miles, but as the distance decreased to two miles, the dune disappeared from the display. The contour lines on the VSD, where the dune had been, pulled down to the bottom of the display. The command steering vector did not give a fly-up command and the helicopter would have flown level into the side of the dune if the command had been followed. Large sandy areas were displayed on the HSD as black areas similar to those presented by lakes. After several passes, the Doppler radar broke lock and could not be made to function properly again over the sandy area. The AN/APN-141 radar did not provide returns from sand dunes, and the TF system was unusable over large sandy areas.

The TF system was not evaluated over water. However, it is expected that over a smooth water surface, no energy would be reflected back to the antenna and the terrain following system would command a descent. The pilot would have to ignore the VSD command and "fly his radar altimeter." A secondary mode of TF operation with commands based on radar altitude and rate of change of radar altitude could be used to eliminate this problem. This mode might also be integrated as a partial fail safe feature for overland operation in that it could automatically generate a fly-up command whenever the altitude went below 90 percent of that commanded. This mode could also be used in conjunction with the terrain clearance

display as a backup mode in the event of a VSD failure. The TFR system should incorporate inputs from the radar altimeter to provide TF commands in the event of either the loss of information or erroneous information from the primary radar. (R 8)

Terrain Following Radar Performance in Adverse Weather

One flight (No. 60) of one hour's duration was flown to evaluate TFR performance in adverse weather conditions. Light to moderate rain showers with visibility from one to five miles were flown through.

In the ground map mode, the HSD presented a very adequate display of rain showers and thunderstorm cells for weather avoidance. The HSD was only evaluated on ranges of 18 NM or less. The 35-NM range was not evaluated. Rain showers and thunderstorm cells were clearly visible on the HSD and could be easily circumnavigated by use of the track strobe. Use of the HSD for ground mapping in the vicinity of rain showers was found to be slightly more difficult. Radar navigation required much more attention because some weather returns obscured large portions of the display. A good knowledge of position was helpful in differentiating other weather returns from mountain returns. The radar was not evaluated in areas of widespread rain such as would be encountered in a weather front. The TC mode was not evaluated in adverse weather conditions. Any complete evaluation of this TFR system for operation in adverse weather would include the testing of the TC mode and the 35-mile range as well as operation in areas of widespread rainfall.

The TF mode was evaluated by flying at 400 feet directly toward and through light to moderate rain showers. When approximately four miles from the rain shower, the command vector began to indicate a climb. This command was followed by the pilot and continued to indicate a climb even at 1,000 feet AGL with relatively flat terrain in front of the aircraft. As the HH-53 neared the base of the cloud, the climb was discontinued to avoid flying into the cloud. It was evident that the TFR system was generating a command, which if followed, would have caused the helicopter to climb up into the cloud. Similar climb commands were noted on four other passes through light to moderate rain showers. On one pass toward a rain shower of moderate intensity, the VSD contours indicated a "false hill" as shown in figure 26. The terrain in front of the helicopter did not correspond to the contour displayed. This "false hill" was attributed to radar returns from the rain shower.

When approaching to within approximately two miles of moderate rain showers, the VSD contour lines became very irregular and severe "spiking" made the VSD unusable. Figure 27 is a photograph of this "spiking" taken from a video tape playback of the flight. The VSD was not usable in this condition. If rain was encountered while terrain following, a pull-up to the minimum safe altitude would have to be made.

Because the fan-shaped beam has an elevation coverage of ± 30 degrees, it is possible that climb commands might be generated by flying under any clouds with heavy water content. These commands might be generated even if it was not actually raining. The PAVE LOW system tested might require major modifications or development effort to provide useful TF information in adverse weather. The AFFTC weather testing was extremely limited and further investigation is warranted to establish more data in adverse weather operation. Following that, a study should be made to

determine the level of effort required, to develop the AN/APQ-141 TFR system into an all-weather system. (R 9)

Terrain Following Without Command Steering

Flights 49-3 and 49-4 were for the purpose of checking the feasibility of one possible degraded mode of operation, namely, no terrain following command symbol. The system was otherwise configured in the same manner as in other flight tests. These two flight tests were flown over the Edwards TFR route No. 2 at 200 feet AGL and a nominal groundspeed of 120 knots. Figures 48 and 49, appendix III, portray the results of these two tests. In both cases the altitude histograms show an undesirable shift toward the lower altitudes with a total of 52 percent of the cases below 180 feet. In both cases the aircraft was much lower than 200 feet AGL when transiting the crest, 130 feet in flight 49-3 and 175 feet on flight 49-4. The pilot started his climb at the correct distance from the hill in both cases, but he did not use a sufficiently high climb rate. The small scale on the VSD and the lack of elevation angle markings contributed to this. The VSD should have 3-, 6-, and 9-degree flightpath markings on each side of the display to be used as a reference. This would not only be an aid to this degraded mode of operation, but would be an aid in terrain avoidance and help the pilot to judge more precisely the flight path being commanded and flown. TF flight without command steering is a feasible backup mode of operation. (R 21)

It must be noted that these tests were over a course that the pilot had recently flown many times with command steering operation. For that reason terrain following at 200 feet AGL without a command symbol may not prove feasible, but should prove feasible at some higher altitude. Further development of the proper techniques to use and testing over unfamiliar courses would be necessary to determine a minimum safe altitude for this mode of terrain following.

FAILURE MODE ANALYSIS

Detection and Display of Failures

The PAVE LOW system tested had only one primary failure indicator. The master TFR failure warning was a red light to indicate a go or no-go condition for the entire system. The light, located in the upper left corner of the instrument panel, illuminated both when a radar failure occurred and when the aircraft was below 80 percent of the commanded altitude. The low altitude warning light should be a separate function. The light was not within the primary view of the pilot and was not noticed on several occasions. The master failure warning light should be relocated to either on the VSD or just above it. The master failure warning system should also include a full fly up command. (R 4, R 5, R 6)

Although the TF/TA radar had a self-test system, several failures were encountered that did not actuate the warning system. On one occasion, a component failure in the TFR system resulted in the TF performance deteriorating to a hazardous degree, yet no failure indications were displayed in the cockpit and all displays appeared to function normally. On other occasions, the red failure light blinked on and off although the helicopter was above the commanded altitude and the TF system functioned normally. In the configuration tested, the master failure warning system was unsatisfactory because serious TFR system failures were not detected.

Isolation of Failures

The PAVE LOW system tested had only one primary failure indicator visible to the pilot. This indicated only a go or no-go condition in the entire system. The logic was that should there be a failure in the TF system, the safest thing would be to climb to a minimum safe altitude. In hostile territory with surface-to-air missiles, climbing might not be the safest thing to do even in the event of TFR failure. Some modes of operation with a reduced capability should be considered as feasible and appropriate fault isolation to indicate a possible mode of TF operation should be provided. For example, in the event of a failure of the TF computer, the pilot can still fly in a TF mode by keeping the cross above all the contour lines. To do this would require that the pilot have some knowledge that the TF computer had failed and not the velocity vector circuit components. The Norden AN/APQ-141 radar had built in fault detection logic and indicators available as part of the system. However, the indicators were all installed in the cargo compartment and could not be seen from the cockpit for any real time malfunction analysis. The master TFR system failure warning light was not sufficient to isolate malfunctions. In addition to the master failure warning light, an additional malfunction indicator panel should be added. This should be readily visible to the pilot and designed to aid him in making a decision as to what degraded modes of operation are feasible as an alternative to climbing to a higher altitude. **(R 7)**

LOW LIGHT LEVEL TELEVISION SYMBOLOGY

The LLLTV was equipped with symbology during the PAVE LOW program. Two modes of operation were available, one for search and the other for hover operation. Both modes greatly reduced the crosscheck required during the approach and hover phases of the LNRS mission. The reduced workload and additional information on the LLLTV display promoted increased pilot confidence and allowed much more precise hover control. The symbology should be added to the LNRS as soon as possible. **(R 32)**

Search Mode

Several LNRS approaches to a hover were made to evaluate the symbology. The search mode was used throughout the pattern and final approach. The symbology presented all the information needed by the pilot to monitor the approach with the exception of distance-to-go to the survivor. The distance to go was obtained from the Doppler radar control panel and was called out by the copilot. This was the same procedure used in the standard LNRS helicopter. The use of the symbology greatly reduced the span of crosscheck required, reducing pilot workload and increasing pilot confidence.

Location of the camera/symbology control panel was unsatisfactory. The panel was located on the forward right side of the lower console and required that the pilot operate the camera elevation control. This was normally accomplished by the copilot on the standard LNRS aircraft. Operating the camera elevation detracted from the pilot task. In the production configuration, this control panel should be located in the same place as the standard LNRS auxiliary camera control panel. **(R 33)**

The camera elevation control knob rotated in the wrong direction. All pilots that operated the system instinctively used a counter-clockwise

motion to depress the camera elevation angle. The rotation of the camera elevation control knob should be reversed so that a counter-clockwise rotation of the control knob depresses the camera elevation angle. (R 34)

The camera boresight symbol obstructed the view of the intended hover location. This symbol served no useful purpose in any mode.

The velocity vector cross obstructed the view at the top of the display during many search operations and during the final approach. The camera was often 15 degrees below the flight path of the helicopter during these operations which resulted in the cross moving to the top of the display and blinking. This was distracting and blocked the view of the pickup site while on final approach.

Hover Mode

In the hover mode, the symbology was of the greatest value. All data required by the pilot was displayed on the LLLTV display. Ground speed and direction were clearly indicated by the velocity vector cross, allowing more precise control with much less pilot workload in interpreting aircraft movement. Without the symbology, speed and direction of movement had to be determined by comparing and interpreting the movement on the LLLTV and the displacement of the needles on the hover indicator. This was a confusing, tiring task that could induce vertigo. The numerics allowed the other parameters to be noted at a glance without losing sight on the LLLTV screen.

The camera boresight symbol obstructed the view of the survivor in the hover mode. This symbol did not contribute to the mission and hindered precise location of the helicopter over the spot by blocking view of it.

The velocity vector cross jumped continually in a lateral direction. At times the lateral movement was so pronounced that two vertical lines 1/4-inch apart were visible. The double image of the vertical line was distracting.

Symbology Modifications

During the flight test program, AFFTC and MAC (ARRS) pilots discussed several changes to the symbology, that both felt would be desirable. Contractor personnel stated that the changes could be quickly accomplished with no loss of flight test time. These changes were implemented, and a short flight test evaluation of the results was made. The following items are a summary of these changes and their evaluations.

The vertical velocity range was ±3,000 fpm. This range was too large and a smaller range was desired. The vertical velocity scale was reduced to ±1,500 fpm and it was displayed in the hover mode as well as the search mode. Sufficient time was not available to fully evaluate this change, but preliminary indications are that it would be desirable. A further evaluation of the vertical velocity display range is necessary so that an optimum range for this parameter can be determined. (R 35)

The symbology mode was changed by moving the mode selector switch from search to hover or vice versa. At the termination of an approach to a hover, the pilot controlling the camera had to remove his hand from the camera elevation control to change the mode selector switch from search

to the hover symbology mode. This occurred at a critical phase of flight. To eliminate locating and operating an additional control at this time, the symbology mode changeover was incorporated in the camera elevation control system. This automatically changed the symbology from search to hover mode as the camera angle passed minus 90 degrees. Although changing modes from search to hover at minus 90 degrees camera elevation was too late, the automatic changeover was highly desirable. An automatic symbology mode changeover should occur at minus 75 degrees of camera elevation in the production item. **(R 36)**

The camera boresight symbol was eliminated. The loss of the symbol had no detrimental effects and the improved visibility thus obtained was considered beneficial, especially in the hover mode. The camera boresight symbol should be eliminated from the LLLTV symbology. **(R 37)**

An ON-OFF switch was provided for the velocity vector cross in the search mode. This allowed the cross to be removed from the display at the pilot's discretion. This was especially beneficial when the cross was obstructing the particular area being viewed. The ON-OFF switch should be incorporated in the LLLTV symbology controls. **(R 38)**

AIRSPEED AND ALTITUDE CALIBRATION

Because of the removal of the refueling boom and the addition of the PAVE LOW radome, it was necessary to determine the position corrections for airspeed and altitude indicators. The tests were conducted in accordance with the tower flyby method described in reference 1. Figure 50, appendix III, presents the results of these tests.

GENERAL EVALUATION

The TF range gate was set at 30,000 feet. Targets beyond this range would not generate a climb command, regardless of their height. Based upon a 6-degree maximum climb rate, the PAVE LOW system could not safely transit a mountain with a peak in excess of 3,000 feet AGL and a terrain slope greater than 6 degrees. This was not a deficiency, but a design limitation considered acceptable as an operational limitation. Careful flight planning and navigation would prevent this from being a hazardous limitation.

The radar set would not operate above 8,000 feet pressure altitude. Each time operation was attempted above 8,000 feet pressure altitude, the radar set operated briefly, then shut down. This was attributed to the unpressurized magnetron. A production TF/TA radar for the LNRS helicopter mission should operate normally up to the aircraft ceiling. **(R 11)**

The command steering did not provide turn lead information. When turning toward hills, climb information for the actual flight path was not provided. Since a climb had to be started about 2 miles from a 1,000-foot hill to clear it using a 6-degree climb angle, it would be possible to turn into a hill over which the helicopter cannot climb. The pilot was unaware of this until the aircraft track was toward the hill, allowing the TF system to compute the required climb angle. This was a problem when maneuvering in rolling terrain as the climb information was continually late. The TFR system should incorporate turn lead information valid for turn rates using bank angles up to 30 degrees at 80 KTAS or 8 degrees per second. **(R 14)**

The TF system command steering did not provide adequate lateral clearance from obstacles. Although the lateral clearance displayed on the VSD appeared adequate, the actual distance from the helicopter to the hillside was estimated at 50 to 100 feet. This was much too close for night/weather operation as the nearest terrain displayed on the VSD was 1/4 mile in front of the helicopter. Sufficient guidance should be provided on the VSD command steering to fly the helicopter over all obstacles within 500 feet of the flight path. (R 3)

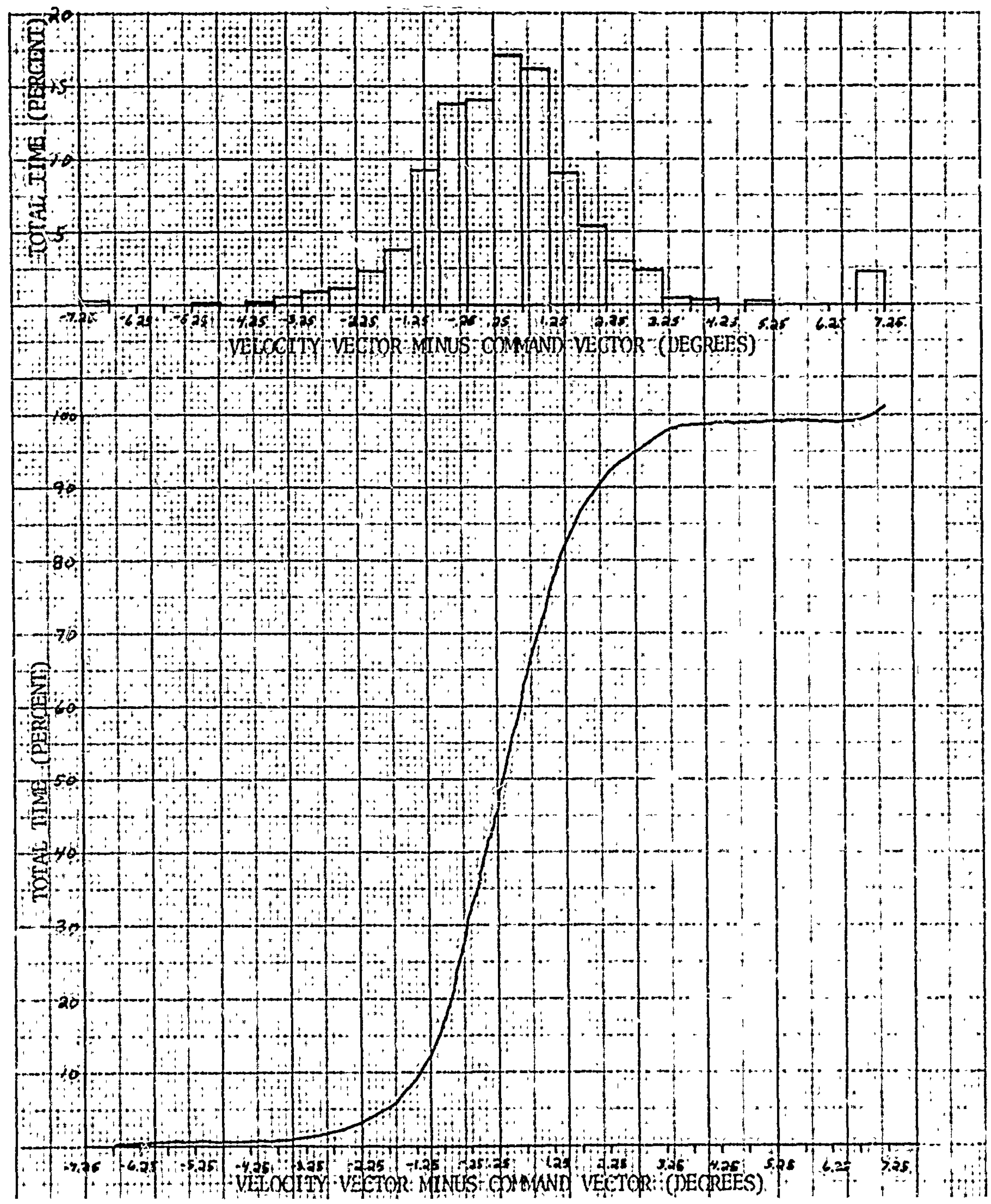


Figure 12 Velocity Vector Minus Command Vector

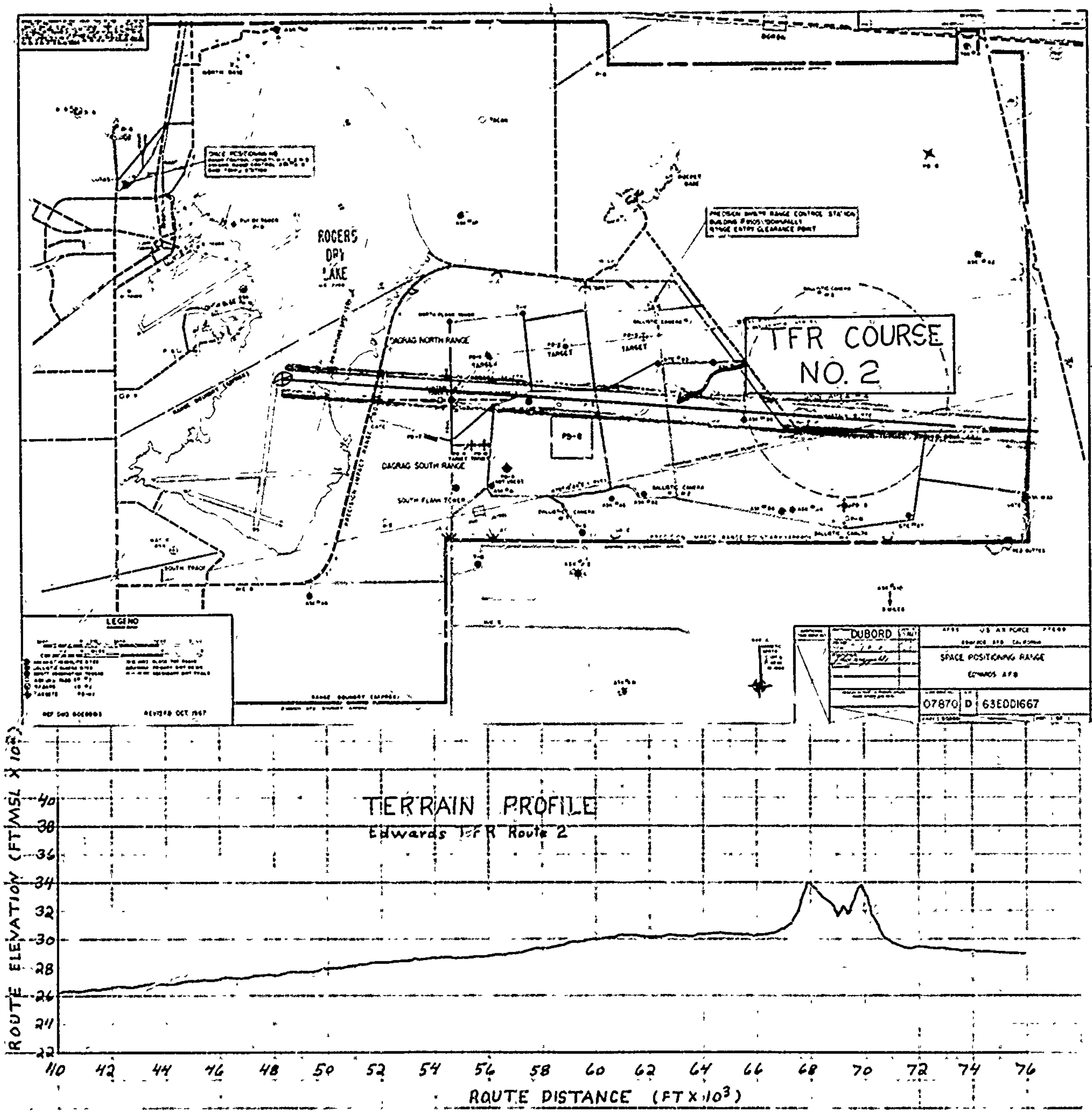


Figure 13 Edwards TFR Route 2

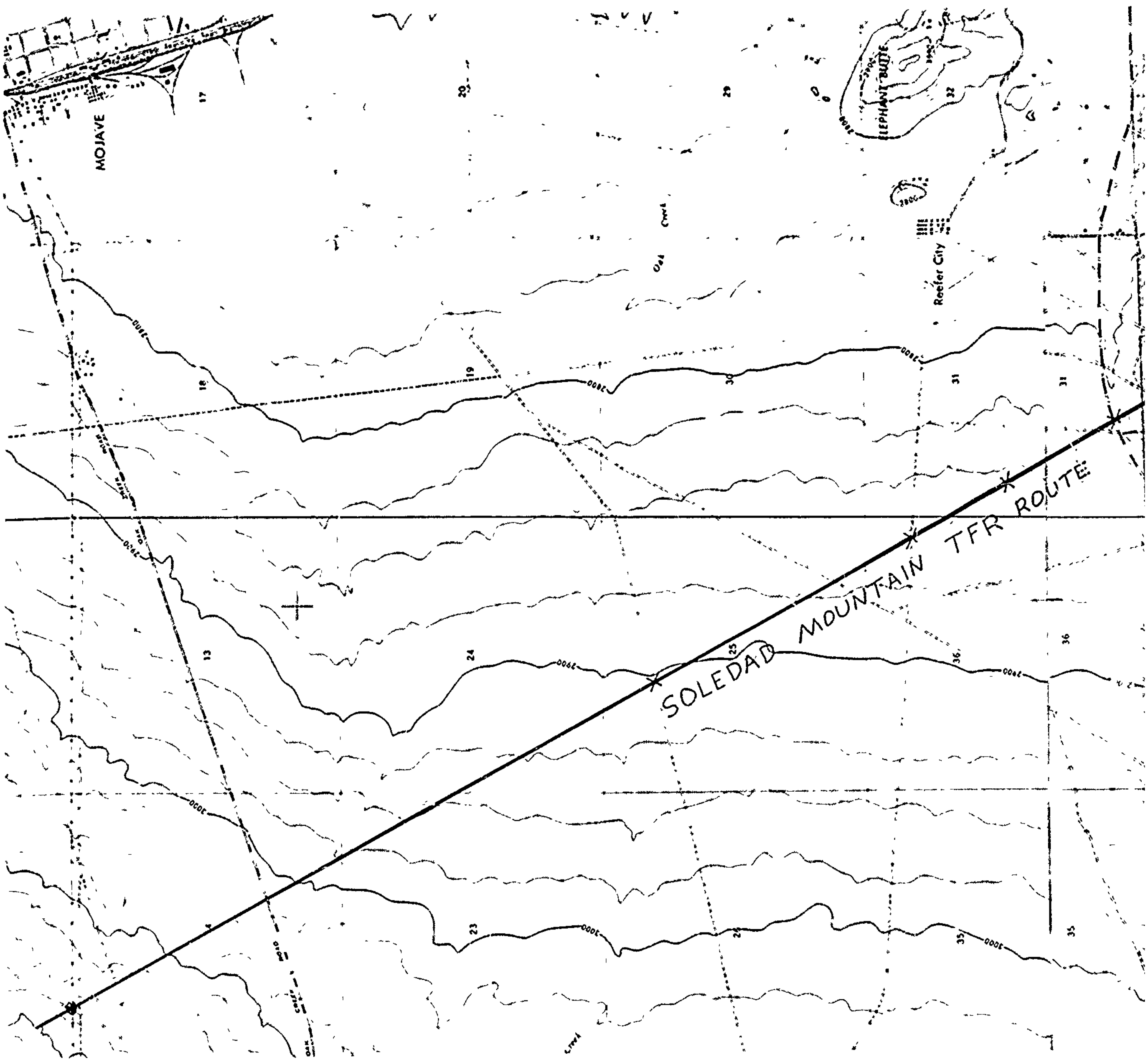


Figure 14 Soledad Mounta

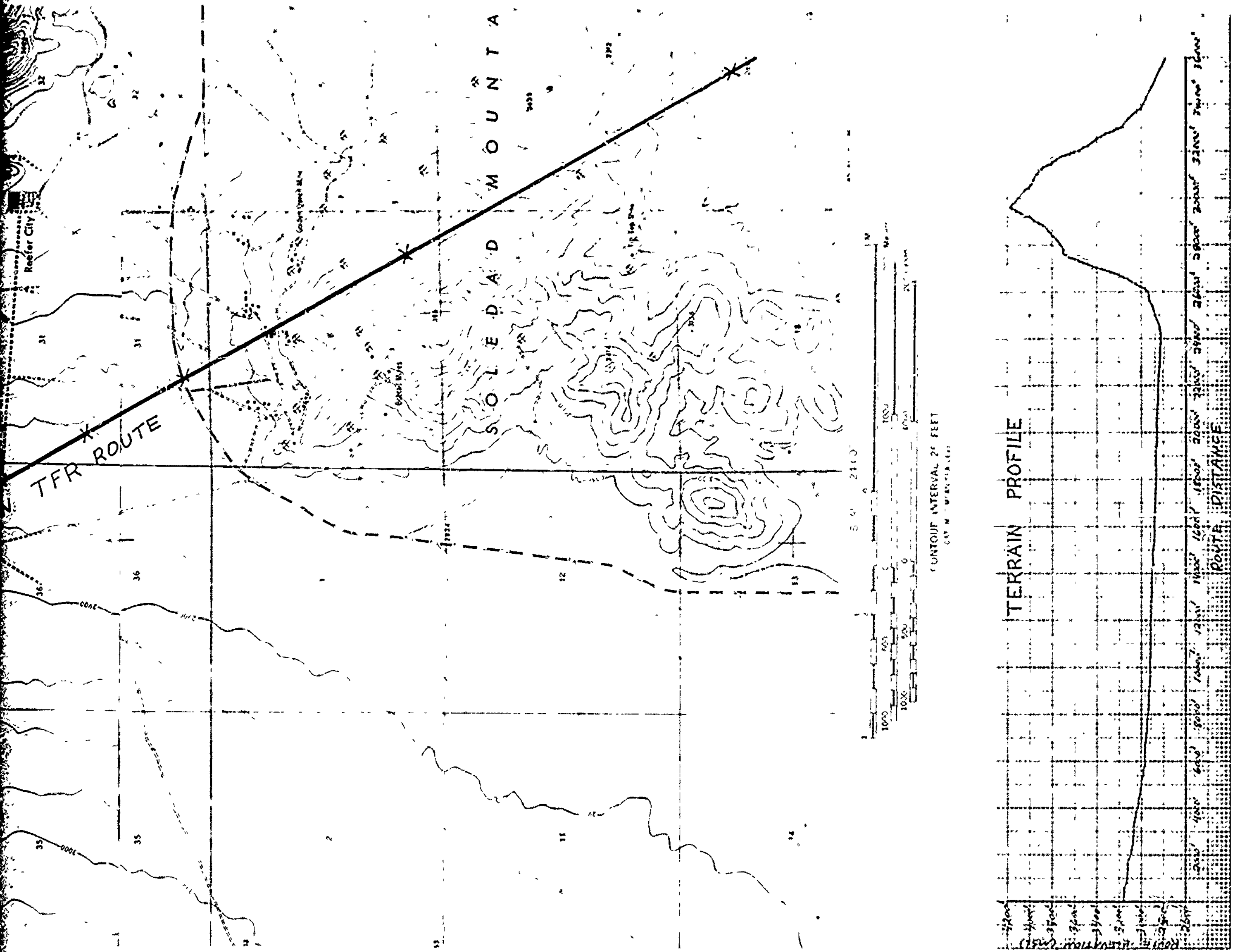


Figure 14 Soledad Mountain TFR Route

2

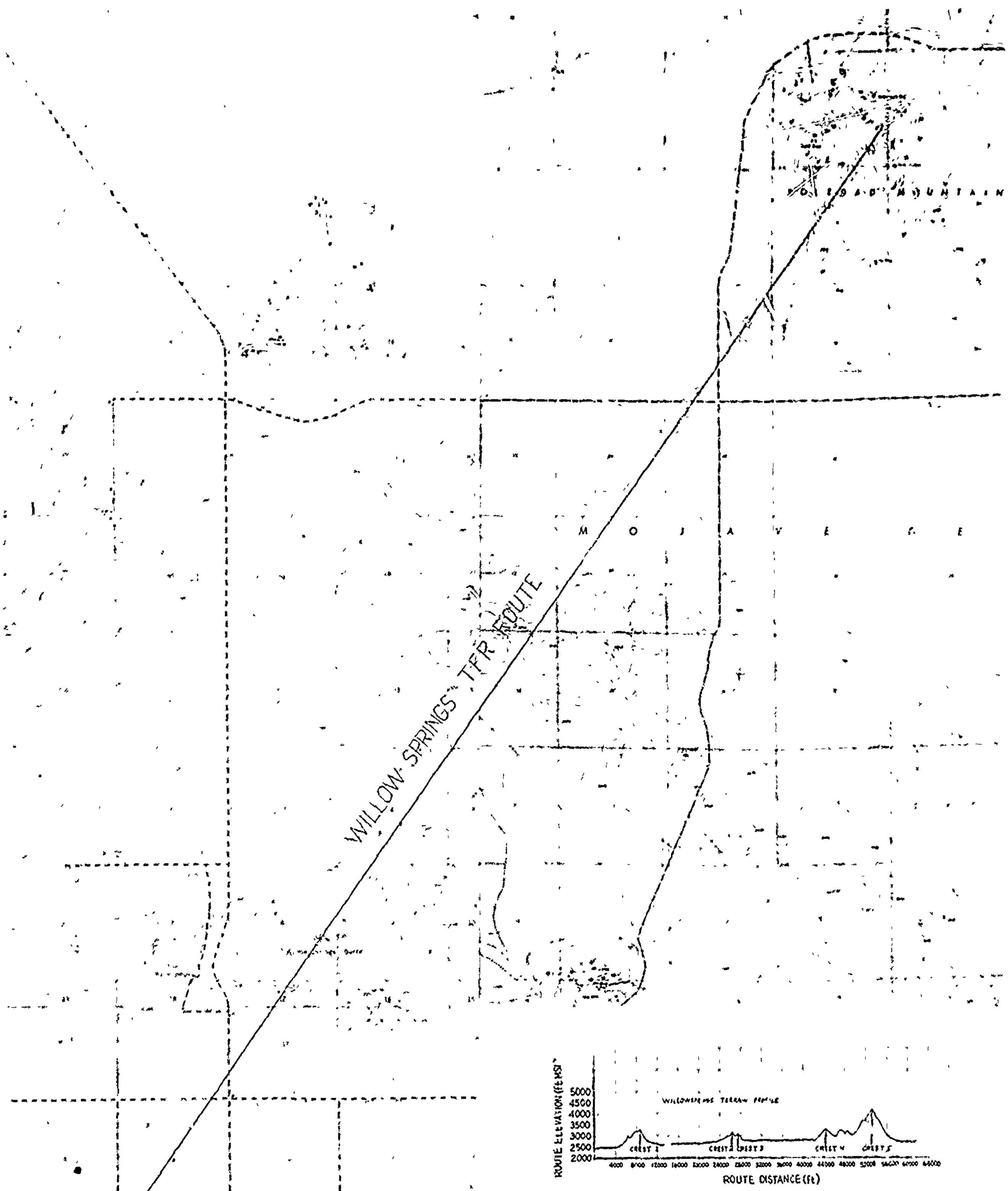


Figure 15 Willow Springs TFR Route

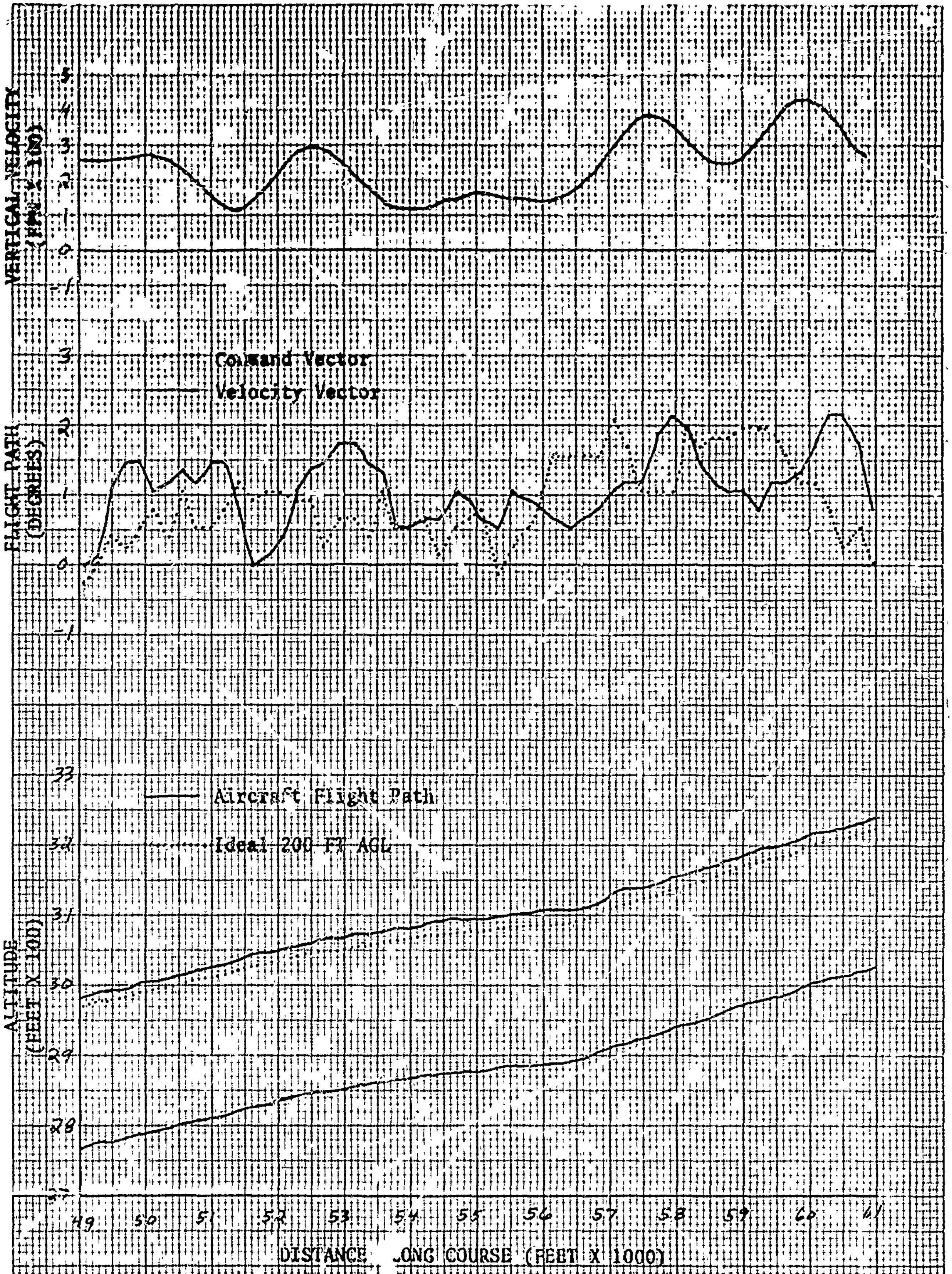


FIGURE 16 FLIGHT 49-1 SMOOTH TERRAIN PERFORMANCE

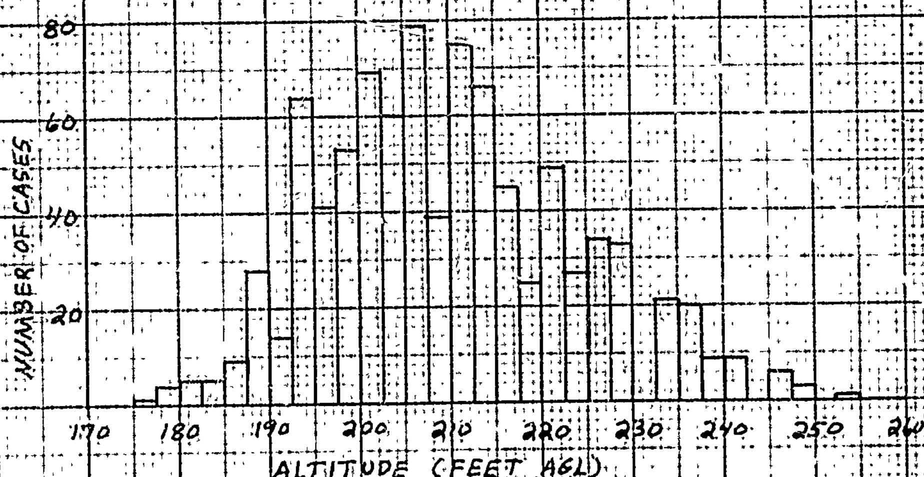
FLAT PORTION OF HAYSTACK TFR COURSE

[illegible] = 200 FT

COMMAND STEERING

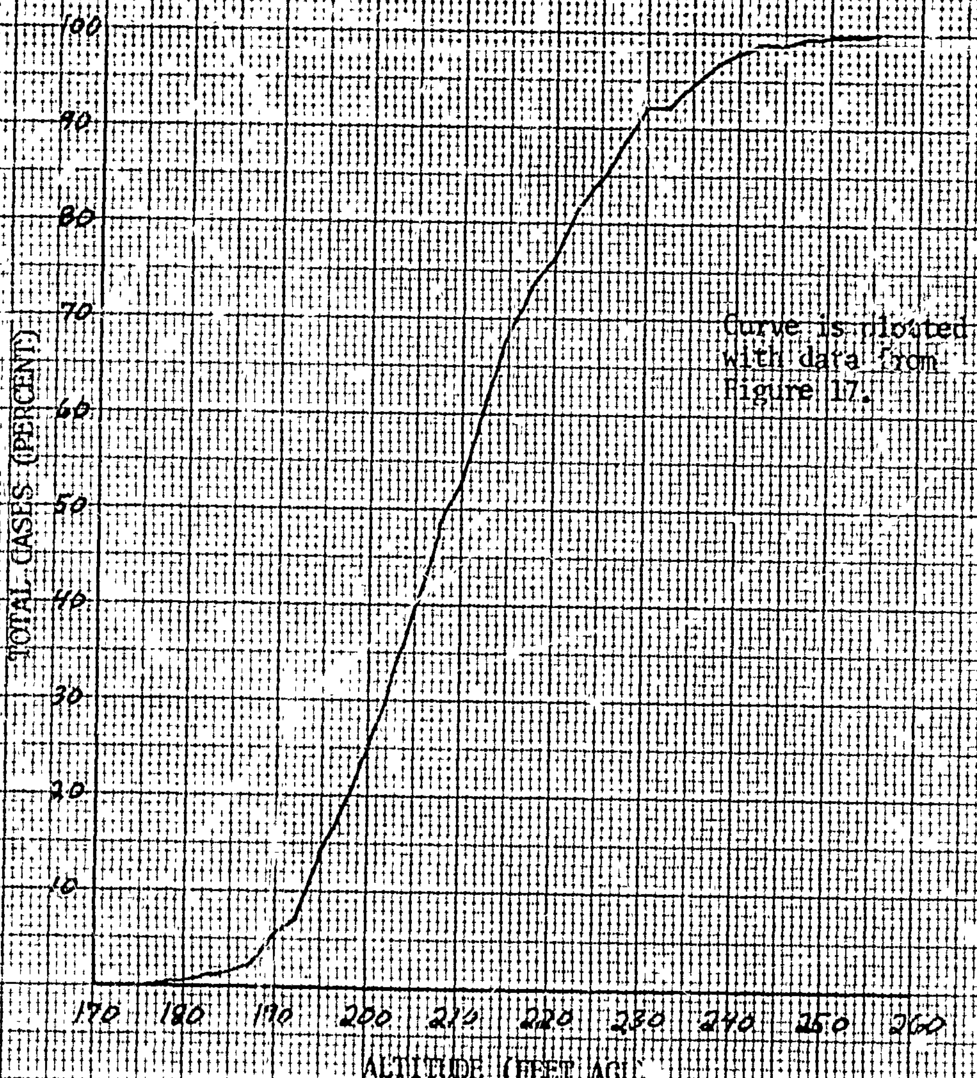
GS = 120K

SUMMARY DATA FROM SEVEN FLIGHTS



HISTOGRAM ALTITUDE OVER SMOOTH TERRAIN (200 FT AGL)

FIGURE 17



CUMULATIVE DISTRIBUTION ALTITUDE OVER SMOOTH TERRAIN (200 FEET AGL)

FIGURE 18

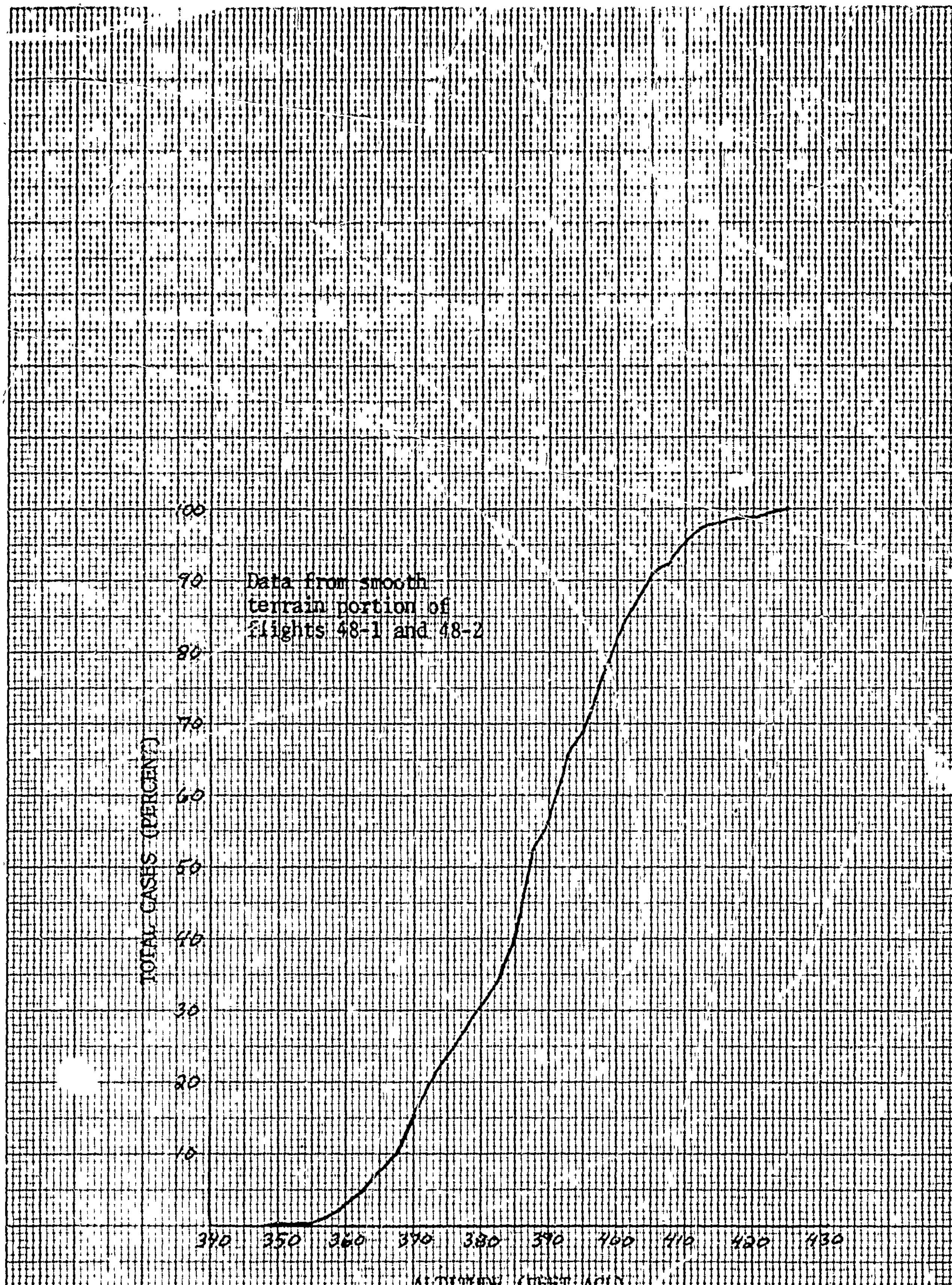
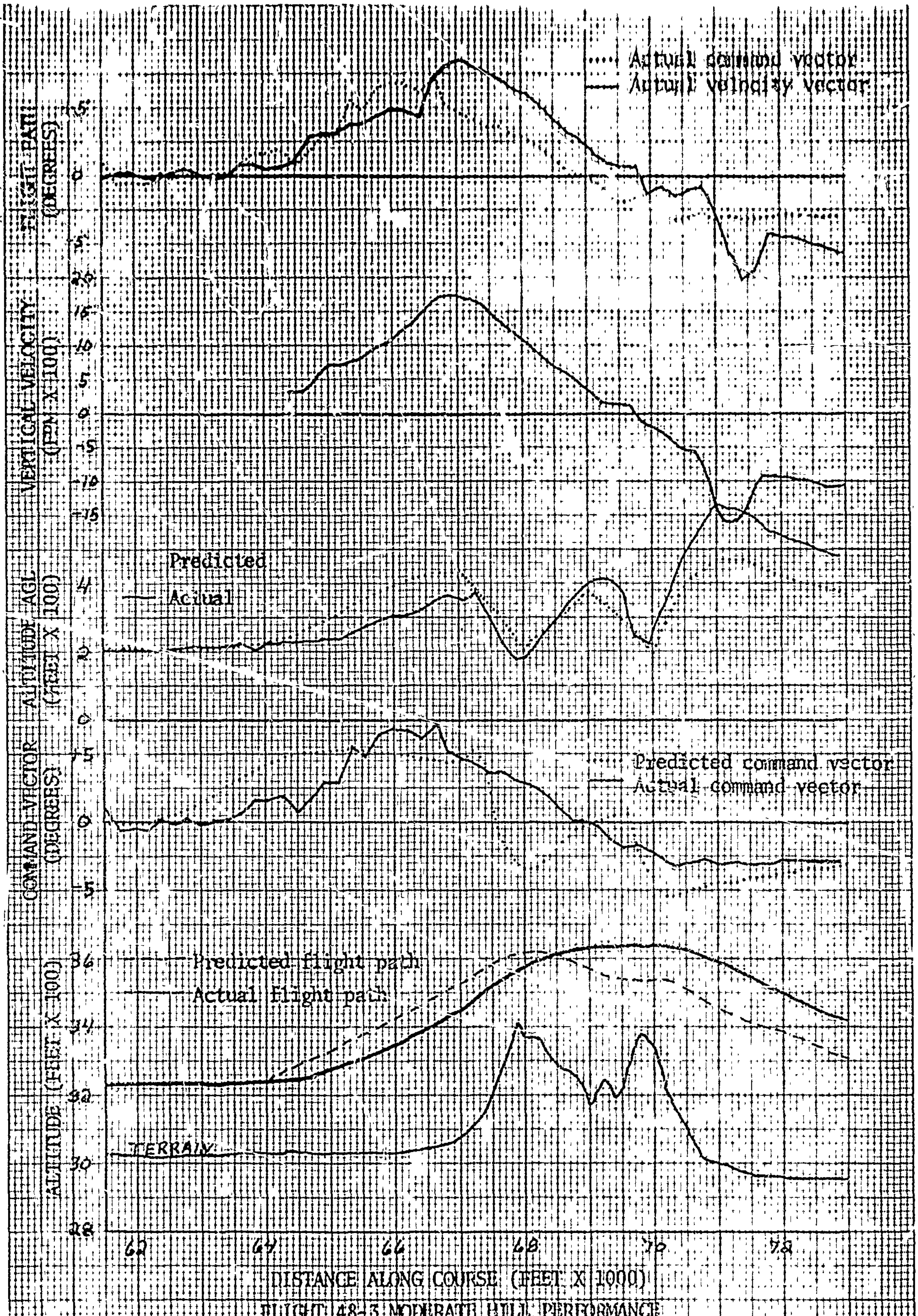


FIGURE 19 CUMULATIVE DISTRIBUTION ALTITUDE OVER SMOOTH TERRAIN (400 FEET AGL)



FLIGHT 48-3 MODERATE HILL PERFORMANCE

FIGURE 20

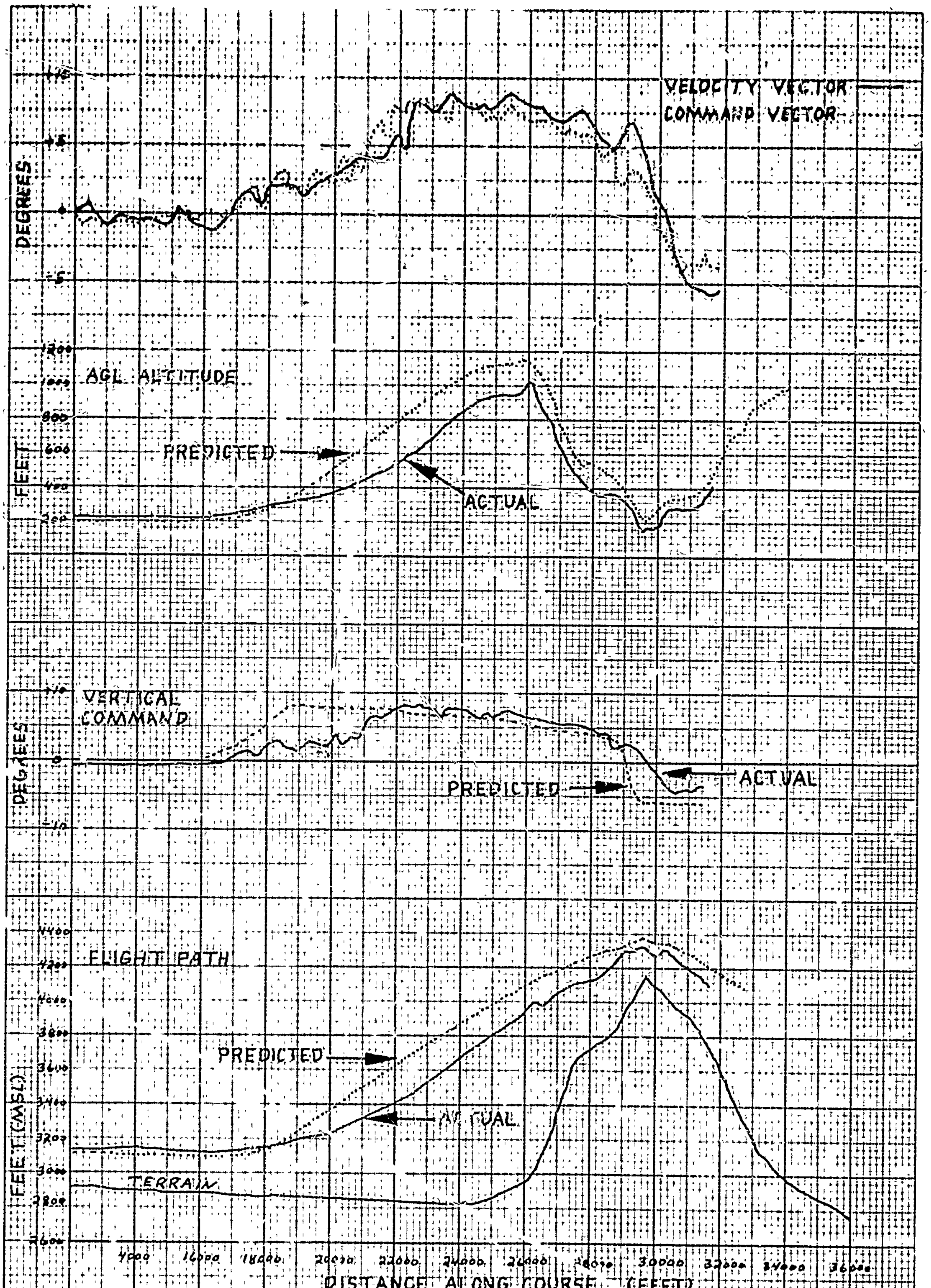


FIGURE 21 FLIGHT 48-7 RUGGED MOUNTAIN PERFORMANCE

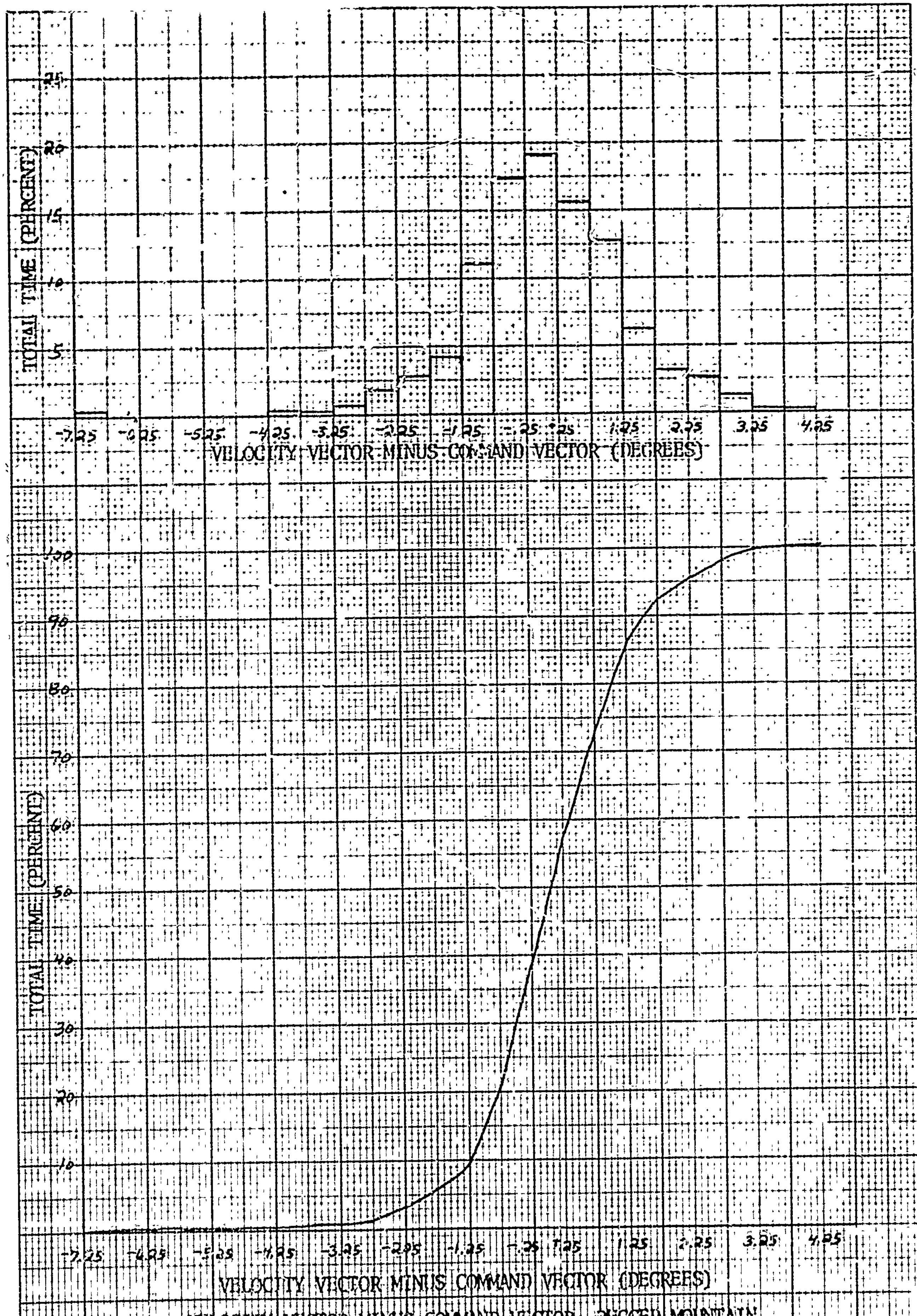


FIGURE 22 VELOCITY VECTOR MINUS COMMAND VECTOR, RUGGED MOUNTAIN TERRAIN (200 FT AGL)

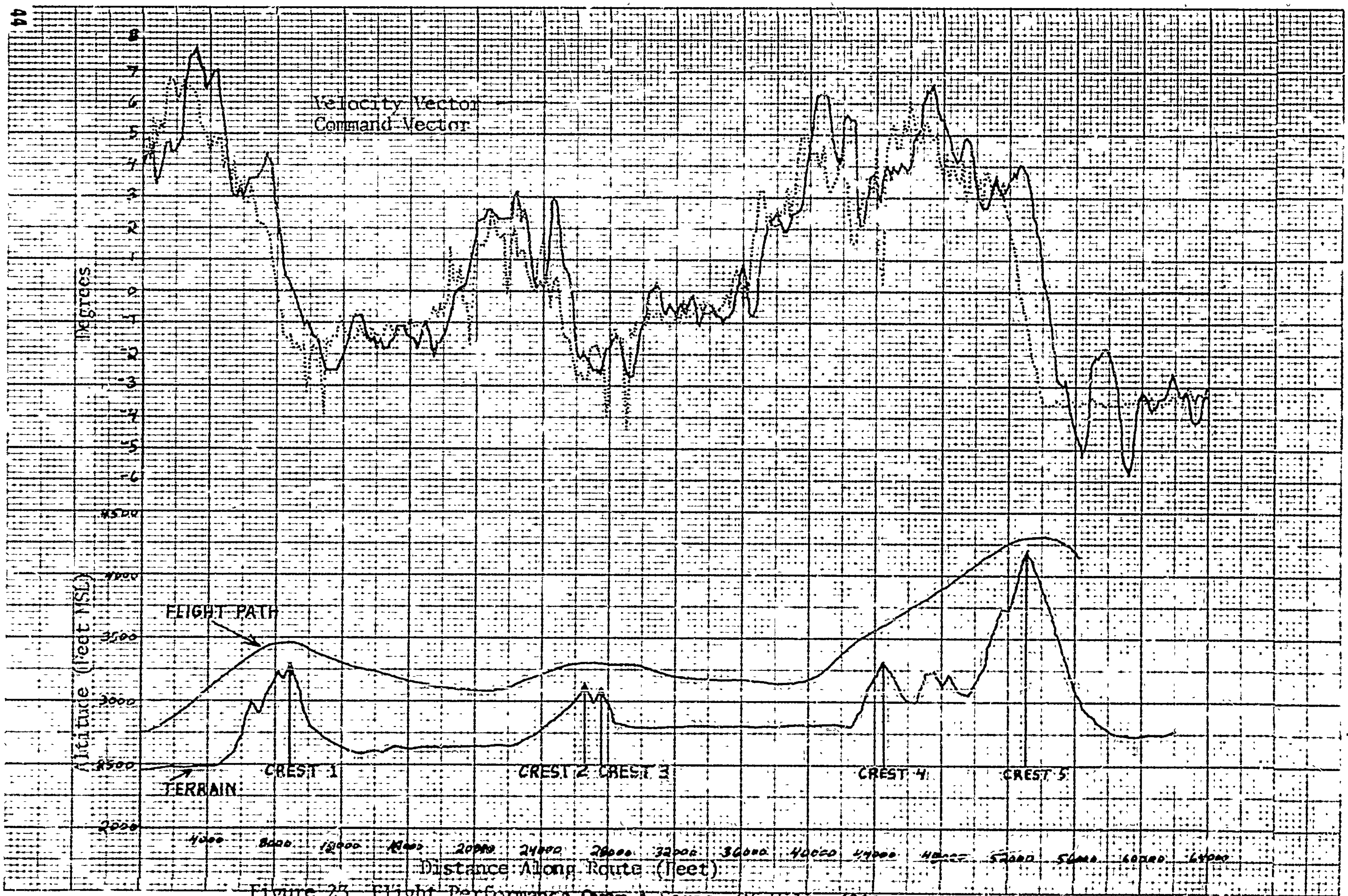
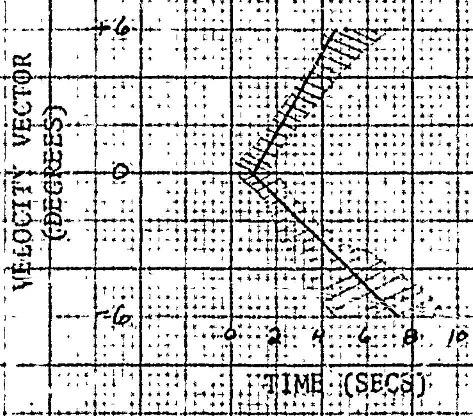


Figure 23 Flight Performance Over A Series Of Hills (200Ft AGL)

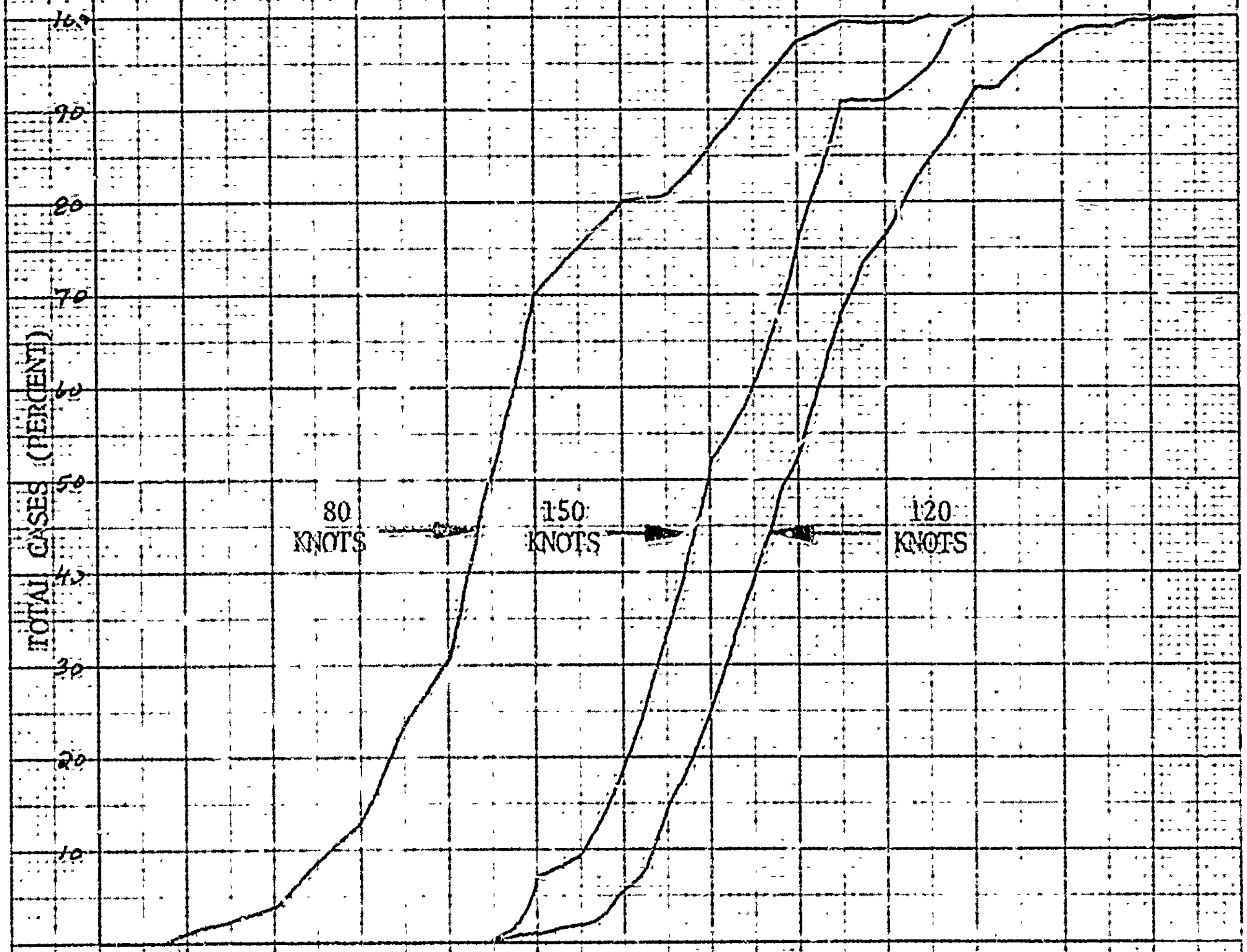


Solid line indicates average response to step command inputs of +6° and -6°

Shaded area is envelope of all test cases

Dotted line represents step input commands

FIGURE 24 AVERAGE PILOT/AIRCRAFT RESPONSE



CUMULATIVE DISTRIBUTION ALTITUDE AT VARIABLE SPEED OVER SMOOTH TERRAIN

FIGURE 25

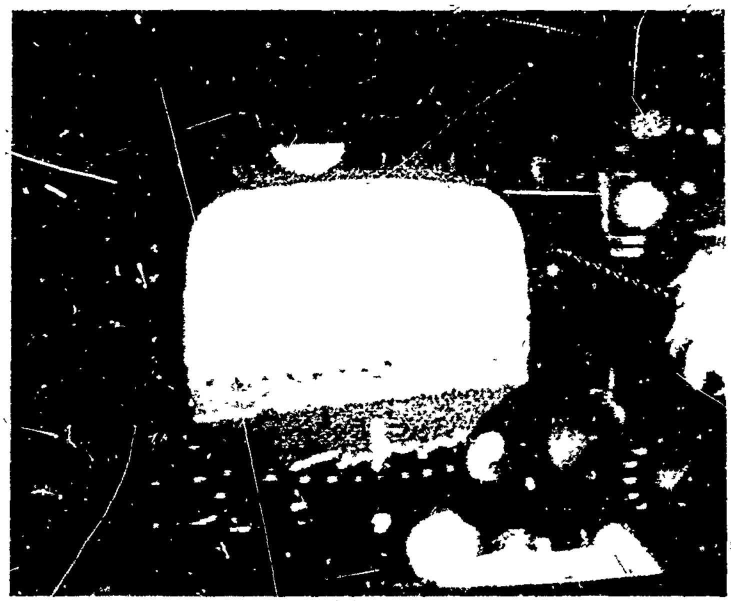


Figure 26 "False Hill" Attributed to Weather Returns

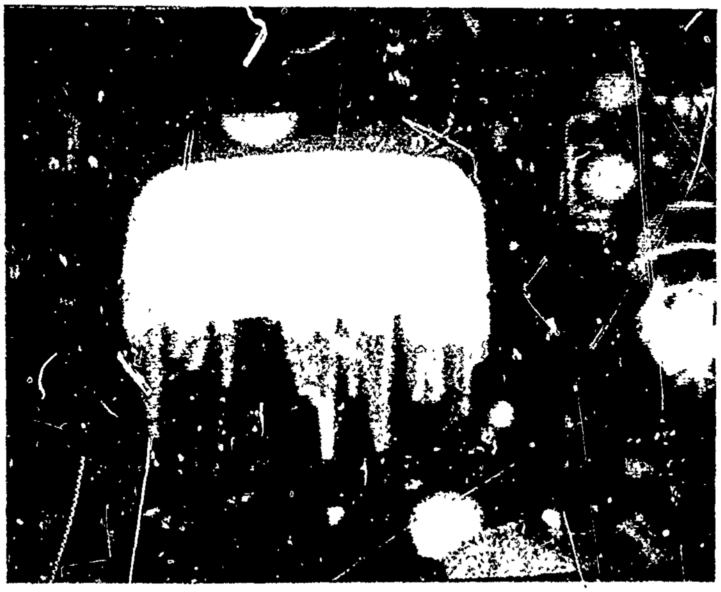


Figure 27 "Spiking" on VSD Attributed to Weather Returns

CONCLUSIONS AND RECOMMENDATIONS

The overall impression of the TF/TA radar was that it provided an increased capability to perform the night recovery mission. The "shades of gray" display provided as part of the PAVE LOW program was exceptionally well suited to the manual terrain following and terrain avoidance mission. However, numerous deficiencies seriously degraded the capabilities of the TFR system. Among the more significant discrepancies were: insufficient terrain clearance over obstacles, a descent rate that was too slow, insufficient horizontal clearance from obstacles, inability to operate in adverse weather and over certain terrain conditions, and an unsatisfactory failure detection and warning systems. Further development and testing is required before a production model system can be achieved.

The symbology addition to the LLLTV display also provided a significant improvement in the capability to perform the night recovery mission. Pilot workload was reduced and the symbology promoted increased pilot confidence and allowed much more precise hover control.

Some of the deficiencies occurred because the AN/APQ-141 radar was designed for the Army Cheyenne helicopter and redesign for this program was held to a minimum. Other deficiencies in the performance of the radar should have been corrected for this evaluation, but development of the system was continually delayed by Doppler malfunctions, and development was terminated on 31 October 1972.

TERRAIN-FOLLOWING RADAR SYSTEM PERFORMANCE

The TFR system performance over hills and mountains was unsatisfactory. The climb commands were not presented on the VSD soon enough to safely transit a moderate hill or rugged mountain without exceeding a six-degree climb. As a result of this deficiency, the climb command and the velocity vector consistently exceeded the desired six-degree maximum climb rate and the altitude at the crest of the hill was consistently too low. The helicopter clearance from the crest of a moderate hill ranged from 151 to 190 feet when a commanded altitude of 200 feet was selected. This was unsatisfactory.

1. A production TFR system should consistently be capable of maintaining the clearance altitude at not less than 90 percent of the commanded value and not more than 120 percent of the commanded altitude when transiting the crest (page 20).

The actual aircraft altitude was below the desired altitude in climbing over the crest and above the desired altitude in descending behind the crest. The commanded rate of descent was unsatisfactory in that it was too slow.

2. The commanded rate of descent for a production TF/TA radar should be 1,500 to 1,800 fpm until the aircraft is within 300 feet of the set clearance and then reduced to a rate no faster than 1,000 fpm (page 20).

The TFR system vertical commands did not provide adequate lateral clearance from obstacles.

3. Sufficient guidance should be provided on the VSD command steering to fly the helicopter over all obstacles within 500 feet of the flightpath (page 32).

The detection and display of failures within the TFR system was unsatisfactory. The PAVE LOW system had only one primary failure indicator. The master TFR failure warning was a red light to indicate a go or no-go condition for the entire system. Several failures were encountered that did not actuate the master warning light, and on at least one occasion, all other cockpit displays also appeared normal. The master failure warning system was unsatisfactory because serious TFR system failures were not detected. The TFR failure warning light also illuminated when the aircraft was below 80 percent of the commanded altitude.

4. The low altitude warning light should be a separate function (page 29).

The master failure warning light was not within the primary view of the pilot.

5. The master failure warning light should be relocated to either on the VSD or just above it (page 29).

6. The master failure warning system should also include a full fly-up command (page 29).

Operation in hostile territory might make it desirable to continue to fly at low level in spite of certain TFR failures. Some modes of operation with a reduced capability should be considered as feasible instead of only one fully operational mode. The master TFR system failure warning light is not sufficient to isolate malfunctions.

7. In addition to the master failure warning light, an additional malfunction indication panel should be added. This should be readily visible to the pilot and designed to aid him in making a decision as to what degraded modes of operation are feasible as an alternative to climbing to a higher altitude (page 30).

The testing was limited to the vicinity of Edwards AFB, which included only desert type terrain. No testing was accomplished over water, heavily vegetated areas, tall trees, or over snow and ice. The TFR system tested did not provide clearance over transmission lines or isolated towers. The AN/APN-141 terrain following radar would not provide clearance over sand dunes and the terrain following system was unusable over large areas of sand. The PAVE LOW system was not evaluated over water, and the possibility exists that the TFR system would not operate properly over large areas of smooth water surface. A secondary mode of operation based on a radar altimeter, would be a valuable aid to TFR operation over water, and useful as a degraded mode of operation over land.

8. The TFR system should incorporate inputs from the radar altimeter to provide TF commands in the event of either the loss of information or erroneous information from the primary radar (page 28).

The PAVE LOW system was unsatisfactory in TFR operation in light to moderate rain. The system commanded climbs over flat terrain and the displays became unusable when encountering precipitation. The PAVE LOW system tested might require major modifications or development effort to produce useful TF information in adverse weather. The adverse weather testing by the AFFTC was extremely limited.

9. Further investigation is warranted to determine the level of effort required to develop the AN/APQ-141 TFR system into an all-weather system (page 29).

The TFR system performance at 150 knots was only slightly degraded from that at 120 knots. However, the performance at 80 knots was very significantly degraded from that at 120 knots. The TFR system would not provide a satisfactory clearance over moderate hills and performance over smooth terrain was also degraded at 80 knots.

10. The TFR system should be provided with some means of operating at a variety of speeds, both higher and lower than 120 knots (page 26).

The radar set would not operate above 8,000 feet pressure altitude.

11. A production TF/IA radar for the LNRS helicopter mission should operate normally up to the aircraft ceiling (page 32).

TFR performance over smooth terrain was generally rated as good. The TFR performance over smooth terrain at a commanded altitude of 200 feet AGL was excellent, but the terrain following performance at 400 feet AGL over smooth terrain was marginal in that the median altitude was below the commanded altitude.

12. In a production system, the median altitude over smooth terrain should not be lower than the commanded altitude (page 18).

Because this was a manual terrain following system, constant pilot attention to the VSD was required. If a pilot's attention were occupied elsewhere for even as little as 10 seconds, the aircraft could become too close to an obstacle to climb over it with the desired clearance.

13. An audible warning signal should be provided whenever a climb beyond the specified aircraft performance is necessary (page 22).

The predicted climb angle of 6 degrees would allow operation at 13,000 feet density altitude and 40,000 pounds gross weight. However, at the lower altitude and weights tested, the maximum capabilities of the HH-53 were not realized, and this resulted in the helicopter being above the commanded altitude more than would otherwise be necessary.

14. Further investigation of TF profiles should be made to select the optimum TF profile for the LNRS mission (page 20).

15. A pilot selection of a template for either a six degree or an optimum performance climb rate should be provided to better utilize aircraft performance capabilities (page 20).

The command steering did not provide turn lead information when turning toward hills. As a result, climb information was sometimes late.

16. The TFR system should incorporate turn lead information valid for turn rates using bank angles up to 30 degrees at 80 KTAS or 8 degrees per second (page 32).

In flying over a series of hills, the TFR system provided a smooth transition from climbing flight to descending flight and vice-versa. However, the descent rate was too slow and did not allow the aircraft to follow the terrain profile as closely as desired.

The actual aircraft altitude was below the predicted altitude while directly over the crest and above the predicted altitude in descending behind the crest. This ballooning effect resulted in part from the command vector indicating an average command of +2.5 degrees while directly over the crest instead of the desired level flightpath over the crest.

17. The terrain following computer mechanization should be modified so that the command vector does not exceed a positive one-degree climb when directly over an obstacle (page 20).

A very limited investigation of the pilot/aircraft response to step function type command inputs indicated the response was essentially a delay of one second and then a ramp function up to the commanded value. The TFR system computer smoothed out all commands so as not to present step function type commands. Decreasing the amount of smoothing would serve to improve the terrain following profile.

18. Further investigation of response times and computer command mechanization is warranted. This could lead to reduction of the ballooning effect on the back side of a hill (page 24).

VERTICAL SITUATION DISPLAY

The VSD greatly increased the capability of the LNRS system. The shades of gray contours provided an excellent display that was easy to interpret, uncluttered, and very useful. The VSD was rated as an excellent type of display for terrain avoidance/terrain following flights at low level. However, the command displayed on the VSD had intermittent vertical oscillations which greatly reduced the pilots ability to follow TF commands. The command box jumped vertically about the proper command, especially during the initiation of climb and descent commands. This was unsatisfactory.

19. The vertical oscillation should be eliminated and a smooth command at the initiation of climbs and descents should be provided (page 19).

The VSD display was completely unusable above 3,000 feet AGL and only provided a good display at altitudes less than 1,500 feet AGL.

20. The production model VSD should be configured to provide a valid display at all alitudes (page 16).

TF flight without use of the command vector is a feasible backup mode of operation, but probably not at altitudes as low as 200 feet AGL. Further development of the proper techniques to use and testing over unfamiliar courses would be necessary to determine a minimum safe altitude for this mode of terrain following. The small scale on the VSD and the

lack of any elevation angle markings on the VSD were also contributing factors to the poor performance in operation without the command vector symbol.

21. The VSD should have 3-, 6-, and 9-degree flightpath markings on each side of the VSD to provide the pilot a reference for judging flightpath angles (page 29).

The vertical scale of the VSD was unsatisfactory for TA and TF operation because it did not provide sufficient definition of hills at ranges greater than 2.5 miles.

22. The vertical scale of the VSD should provide better definition of hills at the 2.5- and 5-mile ranges (page 16).

The vertical scale of the VSD was unsatisfactory for manual terrain following because the scale was not adequate to allow the pilot to follow the TF commands precisely.

23. The vertical scale should be improved to allow the pilot to more closely follow the flightpath commanded (page 16).

HORIZONTAL DISPLAY SITUATION

The HSD target definition was satisfactory and the display was very usable for navigation. The combined use of the HSD and VSD were excellent aids in terrain avoidance operations. The terrain clearance mode did discriminate target return presentations on the basis of elevation, however, the terrain clearance plane utilized in the PAVE LOW system did not provide an adequate safety clearance above the terrain.

24. The TC mode should be provided with a clearance plane offset 200 feet below the aircraft (page 15).

The TC mode did not provide a usable presentation on the HSD during turns, which reduced the effectiveness of the TC mode.

25. The production model radar should be provided with an antenna stabilization system (page 15).

The excessive attention required in order to obtain a usable presentation on the HSD seriously detracted from the ability of the pilot to safely accomplish the terrain following task.

26. Future HSD's should be designed to minimize control adjustments necessary to maintain a good quality presentation, especially when changing ranges (page 14).

The brightness control knob was too sensitive and also controlled the intensity of the range marks and course line.

27. A separate control should be provided for the range marks and course line brilliance (page 14).

28. The sensitivity of the brightness control should be reduced to a sensitivity more compatible with the environment of a helicopter (page 14).

The HSD range select knob was also the ON-OFF switch. The display was inadvertently turned off several times when changing ranges. This was unsatisfactory because there was a 5-minute delay for electronic circuit warm-up time before the system could be used again.

29. The range selection/ON-OFF knob should have a press or lift-to-turn feature to turn it off (page 15).

Many of the modes of operation required a high brightness level which resulted in the HSD display being too bright at night.

30. The production radar HSD should have a red filter for night operation (page 15).

The HSD did not present a usable picture at very short ranges. This was undesirable for the final approach to the pickup site.

31. The HSD should have the capability of displaying subjects within a quarter mile of the helicopter on both the 2.5- and 5-mile ranges (page 15).

LOW LIGHT LEVEL TELEVISION SYMBOLOGY

The symbology added to the LLLTV display reduced pilot workload, promoted increased pilot confidence, and allowed much more precise hover control.

32. The symbology should be added to the LNRS as soon as possible (page 30).

The camera elevation control panel was located on the forward right side of the lower console and required that the pilot operate the camera evaluation control.

33. The camera elevation control panel should be located in the same place as the standard LNRS auxiliary control panel (page 30).

The camera elevation control knob rotated in a direction different to the direction normally expected. All test pilots instinctively rotated the control knob in a counter-clockwise direction to depress the camera angle

34. The rotation of the camera elevation control knob should be reversed so that a counter-clockwise rotation of the control knob depresses the camera elevation angle (page 31).

The vertical velocity range used on the LLLTV symbology was ± 3000 fpm. This was unsatisfactory because the range was too large.

35. A further evaluation of the vertical velocity display range is needed so that an optimum range for this parameter can be determined (page 31).

At the termination of an approach to a hover, the pilot controlling the camera had to remove his hand from the camera elevation control to change the mode selector switch from search to the hover symbology mode.

36. An automatic symbology mode changeover occurring at minus 75 degrees of camera elevation should be incorporated in the production item (page 32).

The camera boresight symbol did not contribute to mission accomplishment and hindered precise location of the helicopter over a spot by blocking the view.

37. The camera boresight symbol should be eliminated from the LLLTV symbology (page 32).

The velocity vector symbol obstructed the view at the top of the display during many search operations and during final approach. An ON-OFF switch was temporarily provided for the velocity vector cross in the search mode and was satisfactory.

38. An ON-OFF switch for the velocity vector symbol should be incorporated in the LLLTV symbology controls (page 32).

APPENDIX I
PAVE LOW MISSION SUMMARY

Mission No.	Date	Flt Time (hr)	Objective	Results
1	4/28/72	1.2	Instrumentation checkout	Obtained desired data
2	5/2/72	0.5	Instrumentation and radar checkout	Abort - Intercom problems
3	5/3/72	1.0	Instrumentation checkout and radar checkout	Obtained desired data
4	5/9/72	1.3	Check instrumentation and velocity vector	Velocity vector not stabilized properly
5	5/10/72	0.8	Check velocity vector and determine pilot's response time	Obtained data
6	5/11/72	1.3	Calibrate pilot's response time. Check Terrain Clearance Mode	Obtained data
7	5/12/72	0.8	Align TF computer timing	Obtained data, but not complete
8	5/31/72	1.0	Functional check flight (FCF), rotorhead change	Maintenance required
9	5/31/72	1.0	FCF rotorhead change	
10	6/2/72	0.9	Align Terrain Following computer timing	Aligned system
11	6/2/72	0.6	Checkout TF computer	Obtained data. Modification needed.
12	6/7/72	1.5	First attempt at manual Terrain Following @ Soledad Mt.	MTF worked but not satisfactorily
13	6/9/72	1.0	Manual TF over flat earth and Soledad Mt.	Abort in Flight - MTF computer bandwidth problem
14	6/18/72	2.2	Terrain Following	MTF over flat earth good; Soledad poor
15	6/23/72	1.4	Phase video accuracy check	Did not obtain data

Mission No.	Date	Flt Time (hr)	Objective	Results
16	6/26/72	1.7	Indoctrination ARRS personnel	Satisfactory
17	6/30/72	1.5	Evaluation sensitivity adjustments	OK - Transmitter overheat problems
18	7/5/72	1.5	Phase video accuracy check	No data. Transmitter overheat
19	7/16/72	1.1	Phase video accuracy runs	No data
20	7/18/72	1.8	Phase video accuracy runs	No data - tried stationary in dry lake
21	7/26/72	1.7	Phase video accuracy. Check and TV symbology checkout	Good data
22	7/31/72	1.6	Ground map mode evaluation and TF/TA evaluation	Encountered doppler and LNRS problems
23	8/2/72	1.6	Familiarization for MAC/ARRS Commander	Satisfactory
24	8/3/72	1.6	Familiarization for MAC/ARRS and evaluation of radar and symbology	Obtained evaluation
25	8/7/72	1.4	Indoctrination for other AFFTC pilots and evaluation of LLLTV symbology	Obtained evaluation
26	8/8/72	1.3	LNRS approach using LLLTV and symbology at night	Obtained evaluation
27	8/9/72	1.0	Indoctrination for MAC/ARRS on LLLTV symbology	Incomplete, HSD failed in flight
28	8/10/72	1.5	Indoctrination for MAC/ARRS on LLLTV symbology at night	Satisfactory

Mission No.	Date	Flt Time (hr)	Objective	Results
29	8/16/72	1.7	MTF flight to optimize TF computer	Encountered doppler problem (intermittent)
30	8/22/72	0.3	MTF flight to optimize Terrain Following computer	Doppler inoperative Mission abort
31	8/22/72	[illegible]	MTF flight to optimize TF computer	Climb too steep and pushover too early
32	8/23/72	1.5	MTF check flight on Soledad Mt	No improvement in MTF performance by adjusting push over limiter
33	8/28/72	1.0	Instrumentation check flight over Hay Stack Butte	Abort-TFPIS and Doppler inoperative
34	9/1/72	0.5	Doppler check flight	Abort-Doppler inoperative
35	9/1/72	0.5	Doppler check flight	Abort-Doppler inoperative
36	9/6/72	0.4	Doppler check flight	Abort-Doppler inoperative
37	9/7/72	1.2	Doppler check flight	Doppler satisfactory
38	9/7/72	1.5	MTF check flight on Soledad & flat earth	MTF improved. Maximum climb command 8.2 degrees but pushover too early
39	9/12/72	0.7	Photography flight	Doppler inoperative (Abort)
40	9/18/72	1.4	MTF check flight	Obtained data for analysis
41	9/19/72	0.7	Doppler check flight	Abort-Doppler inoperative
42	9/21/72	1.5	MTF check flight over Soledad Mt	Obtained data for analysis
43	9/25/72	1.4	MTF check flight over Soledad Mt	MTF computer changes for flight 42 [illegible]
44	9/25/72	1.0	MTF check flight over Soledad Mt	Good MTF [illegible] still have pushover too [illegible]
45	9/26/72	1.7	MTF flight over Soledad Mt	MTF computer not working [illegible]

Mission No.	Date	Flt Time (hr)	Objective	Results
46	9/27/72	1.4	TF flight over Soledad Mt	γc max OK but crest too low
47	10/3/72	0.5	TF flight check	Abort-Doppler inoperative
48	10/31/72	2.9	TF check over Soledad Mt and Hay Stack Butte	Obtained data, good flight but too low over crest
49	11/1/72	2.0	TF check to check computation modification	No data, command vector incorrect
50	11/2/72	1.4	System checkout flight for Display Symbol Generator	Satisfactory
51	11/3/72	1.4	System checkout over Soledad Mt	No data, oscillograph inoperative, TERIS altitude only
52	11/6/72	1.6	TF flight over Soledad Mt and Willow Springs route	Oscillograph inoperative. Qualitative evaluation appeared normal.
53	11/6/72	1.5	MAC/ARRS IOT&E flight	Satisfactory
54	11/7/72	2.0	MAC/ARRS IOT&E flight TF evaluation over Soledad	Obtained data
55	11/7/72	1.0	MAC/ARRS IOT&E flight	Abort - Doppler inoperative Symbology familiarization
56	11/8/72	1.4	MAC/ARRS IOT&E flight	Abort - Doppler inoperative Symbology familiarization
57	11/10/72	2.0	MAC/ARRS IOT&E flight TF evaluation over Soledad	Partial data obtained Abort - Doppler inoperative
58	11/10/72	0.5	MAC/ARRS IOT&E flight Night evaluation	Abort - Doppler inoperative
	11/15/72	0.7	Functional check flight Rotor maintenance	Aircraft operationally ready
59	11/15/72	1.2	Doppler radar and TF system evaluation @ Soledad Mt	Obtained data on TF profile

Mission No.	Date	Flt Time (hr)	Objective	Results
60	11/16/72	1.0	Weather evaluation	Obtained limited data
61	11/17/72	0.9	MTF evaluation over Willow Springs Route	Abort due to weather
62	11/18/72	2.7	MAC/ARRS IOT&E TA evaluation	Satisfactory
63	11/20/72	0.5	MAC/ARRS IOT&E	Abort-Doppler inoperative
64	11/21/72	1.6	MAC/ARRS IOT&E approach, hover, and symbology evaluation	Satisfactory
65	11/21/72	1.5	MAC/ARRS IOT&E	TFRIS inoperative. No data obtained.
66	11/21/72	2.0	MAC/ARRS IOT&E Night evaluation	Satisfactory
67	11/24/72	1.4	Effect of ground speed. Variation on MTF.	Obtained data
68	11/27/72	0.4	MTF evaluation	Abort-Doppler inoperative
69	11/28/72	1.3	MTF evaluation at Soledad Mt and Willow Springs Route	Obtained data
70	11/29/72	1.7	MTF evaluation at Soledad	Oscillograph inoperative, no data
71	12/1/72	2.5	Evaluation of MTF over Transmission Line Towers and Sand Dunes	Obtained partial data Doppler intermittent
72	12/1/72	2.5	Evaluation of letdown to MTF flight, and MTF over Soledad Mt and Willow Springs Route	Obtained data
73	12/5/72	1.4	Demonstration flight for MAC/ARRS Commander	Satisfactory

APPENDIX II
INSTRUMENTATION

The PAVE LOW aircraft was instrumented with a Sony Videotape recorder, a terrain following radar instrumentation system (TFRIS), and an oscillograph instrumentation system.

The Sony videotape system was used to record the VSD television display and the HSD radar map displays. The system consisted of a Sony CV-2400 portable video camera and video recorder and a Sony CVM-51UWP TV monitor. The video camera was located on the flight crew cabin bulkhead (figure 1) behind the radar pilot (left seat) and looked over his left shoulder. The video monitor was located on the instrumentation/radar table at the flight test engineer's station (figure 2). This enabled the test engineer to monitor the quality of the video being recorded and to observe the pilot's responses to the radar displays. Intercom audio was recorded on the audio channel of the video recorder to voice annotate the recorded video.

The oscillograph instrumentation system consisted of a CEC model 5-119 oscillograph recorder, a Gulton model EMSE-211 oscillograph signal conditioning assembly, and an Astrodata time code generator with displays. All of the signal conditioning modules, oscillograph, and time code generator were mounted on a shelf under the instrumentation/radar table as shown in figure 11 in the body of the report. The Gulton signal conditioning consisted of various modules that isolated the signal source from the oscillograph and supplied power to the oscillograph galvanometers. A unique feature of the Gulton system was on Auto-Cal cycle that, at the end of a data record, would automatically cycle the instrumentation system through a calibration cycle. The oscillograph system was controlled at the flight test engineer's station at the aft end of the instrumentation/radar table (figure 2).

Table I contains a list of the PAVE LOW instrumentation parameters. Data reduction from the raw oscillograph data to engineering units was a slow, tedious, and largely manual process that hampered the test program. Each flight produced an average of one-half hour of usable recorded data. To convert that amount of data to engineering units, would require about 300 manhours per flight using one sample per second. Because of this, only five or six parameters were chosen to be reduced into engineering units on each flight. Only very coarse spot checks of other parameters were manually obtained. With each flight requiring about 100 manhours of data reduction, there soon occurred a large backlog of data and some data was not reduced until two months after the flight.

The TFRIS consisted of a Spectra-Physics Geodolite 3A laser range finder, a Litton LTN-51 inertial navigation system (INS), and IRIG-B time code generator, and a PCM recording system mounted in a modified TMU-28/B Liquid Agent Spray Tank and a TFRIS control panel. The TFRIS pod was mounted on left sponson instead of the standard 450-gallon fuel tank (figure 3). The TFRIS control panel was mounted at the engineers station (figure 2). For this test the time code generator was removed from the pod and installed on the instrumentation shelf under the instru-

mentation/radar table. The INS supplied the laser range finder with stabilization signals to maintain the laser beam in a true vertical position. The laser beam had an angular freedom of +45 to -15 degrees in pitch and +45 degrees in roll. The laser projected a narrow pulsed beam vertically downwards to the surface and received the reflected laser energy. The length of time for the beam to travel down to the surface and return was measured and converted to an accurate height measurement.

The TFRIS pod system never worked in an entirely correct manner throughout the entire test program. During the early part of the test program, malfunctions in the mirror stabilization system and in the INS prevented proper operation. During the entire test program, the TFRIS pod never provided a correct time history of aircraft velocity. The digital computer output of TFRIS altitude information had many parts where noise in the TFRIS system apparently caused altitude inaccuracies.

The AFFTC Askania system was also used to provide a time history of aircraft position, velocity, and altitude when flying the Edwards TFR Route 2. The latest survey of the Askania system indicated an accuracy of +5 feet within the area of TFR Route 2 up to the crest of Haystack Butte. Comparisons of TFRIS altitude, AN/APN-171 altitude, and Askania-derived altitude were determined during level flight over this portion of the course.

At 200 feet nominal altitude, the laser altitude averaged about 13 feet lower than the Askania. The standard deviation of this difference was approximately 4 feet indicating fairly consistent data. Under the same conditions the AN/APN-171 altitude averaged about 12 feet higher than Askania data. The standard deviation of this difference was approximately five feet, again indicating fairly consistent data. Contributing to the error in the radar altimeter data was the fact that the AN/APN-171 feedhorns were aligned 18 degrees forward of the vertical. This was done by design to eliminate the problem of the AN/APN-171 locking on to the hoist during rescue operation. The 18-degree difference from the vertical implied that the radar altimeter should indicate an altitude 10 feet higher than the true vertical altitude and was also focused on a spot 65 feet ahead of the aircraft while flying at a nominal 200 feet altitude. This was in agreement with the results obtained from Askania - AN/APN-171 altitude comparison. Due to the other problems with the TFRIS data previously mentioned and the approximate equal accuracy, it was decided to use the radar altimeter for all absolute altitude data in the report.

The AN/APN-171 Doppler-derived ground speed averaged 3-1/2 feet per second (or 2 knots) lower than Askania-derived ground speed. The Doppler ground speed was therefore sufficiently accurate so as not to introduce any errors into the TFR system.

Flightpath angle was measured by Askania and compared with the vertical velocity vector recorded on the oscillograph. The comparison of the two was favorable with a maximum difference of 1.2 degrees and a majority of the differences were less than one-half a degree. Figures 4 and 5 portray this comparison. This indicated that no large errors were present in the velocity vector as a result of the small inaccuracies in the Doppler-derived ground speed and in the altitude derived from the AN/APN-171 altimeter.

Figure 1 Instrumentation Television Camera Location

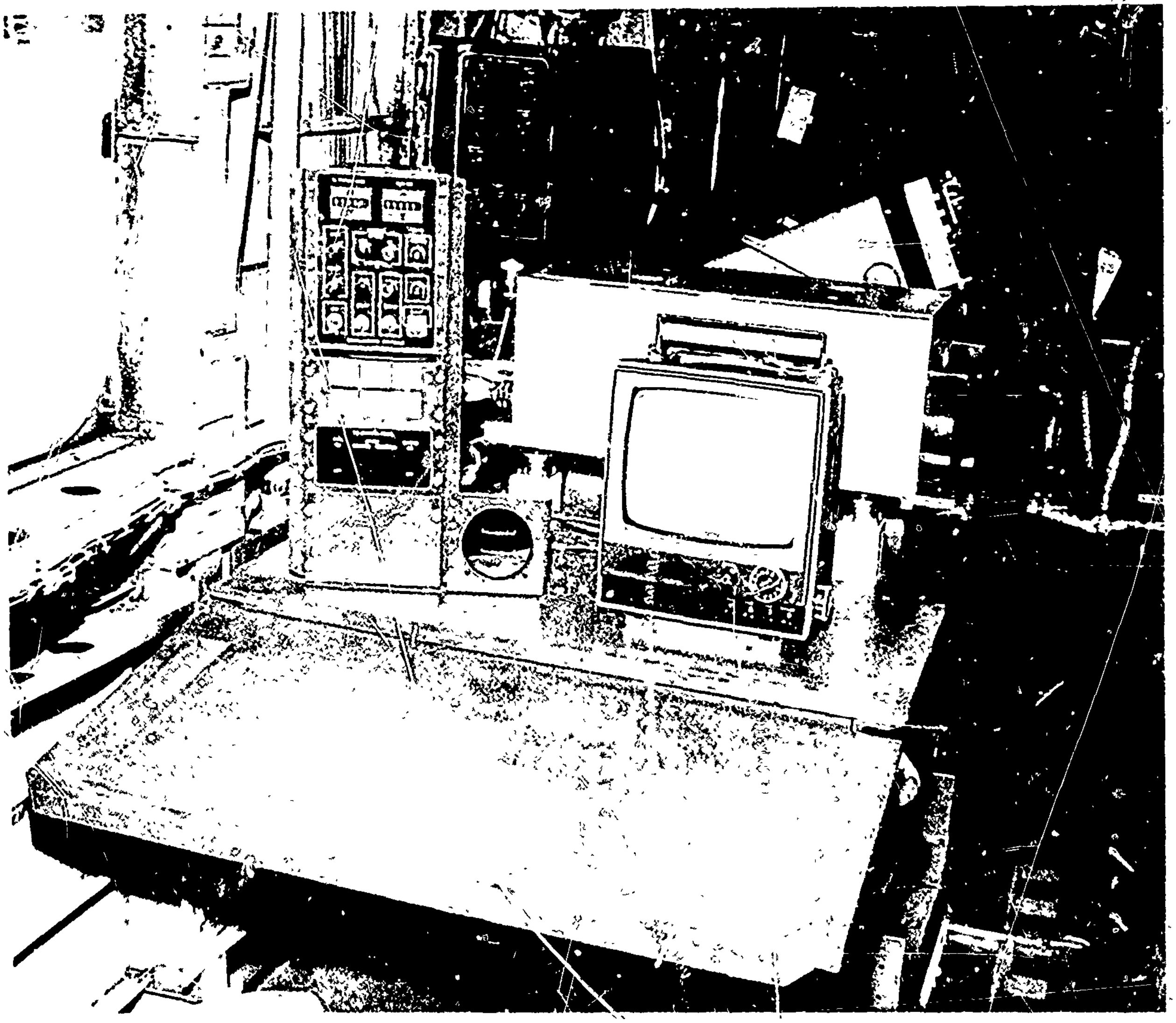


Figure 2 Flight Test Engineer's Station

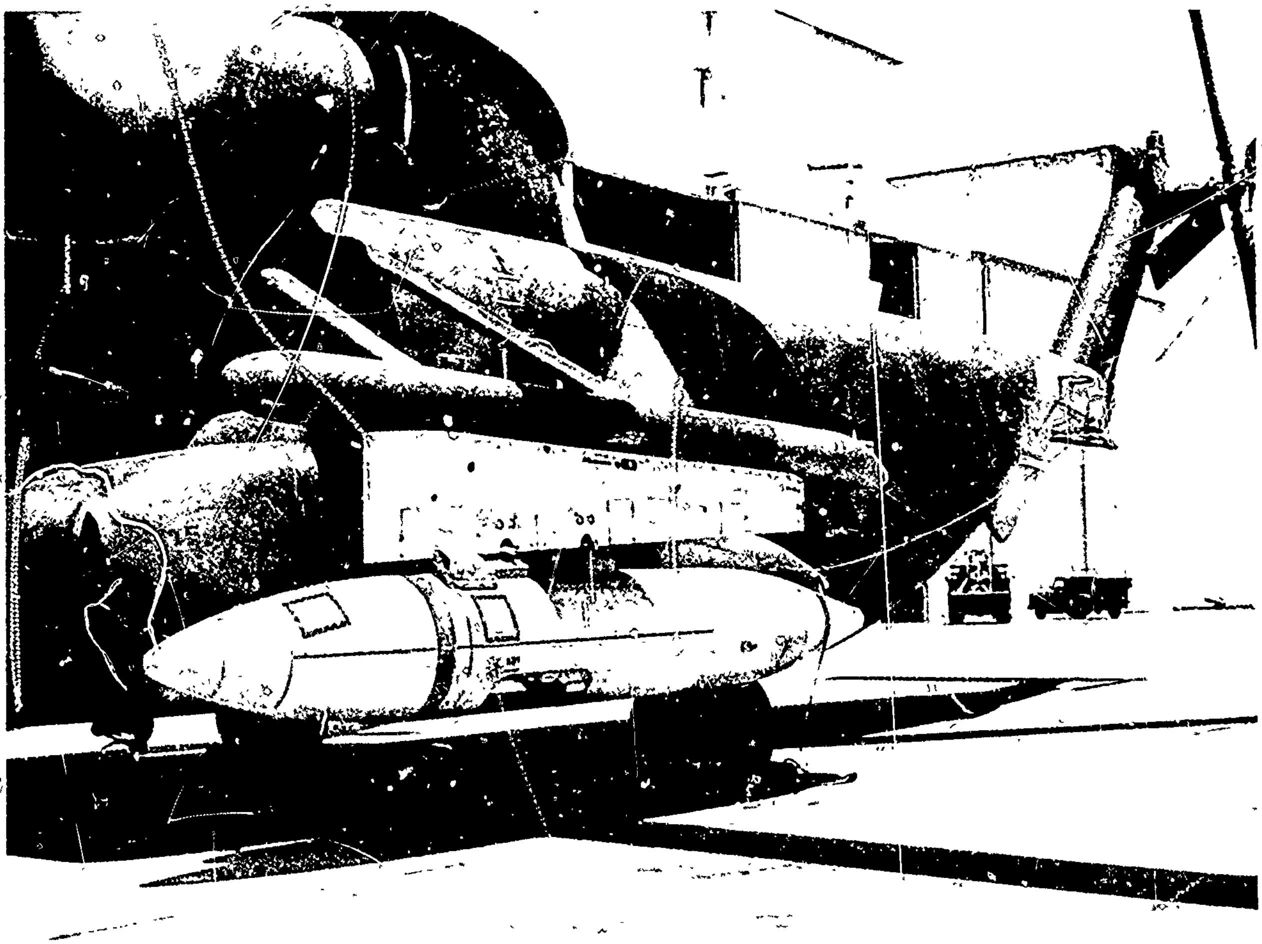


Figure 3 Terrain Following Radar Instrumentation System (TFRIS) Pod Installation

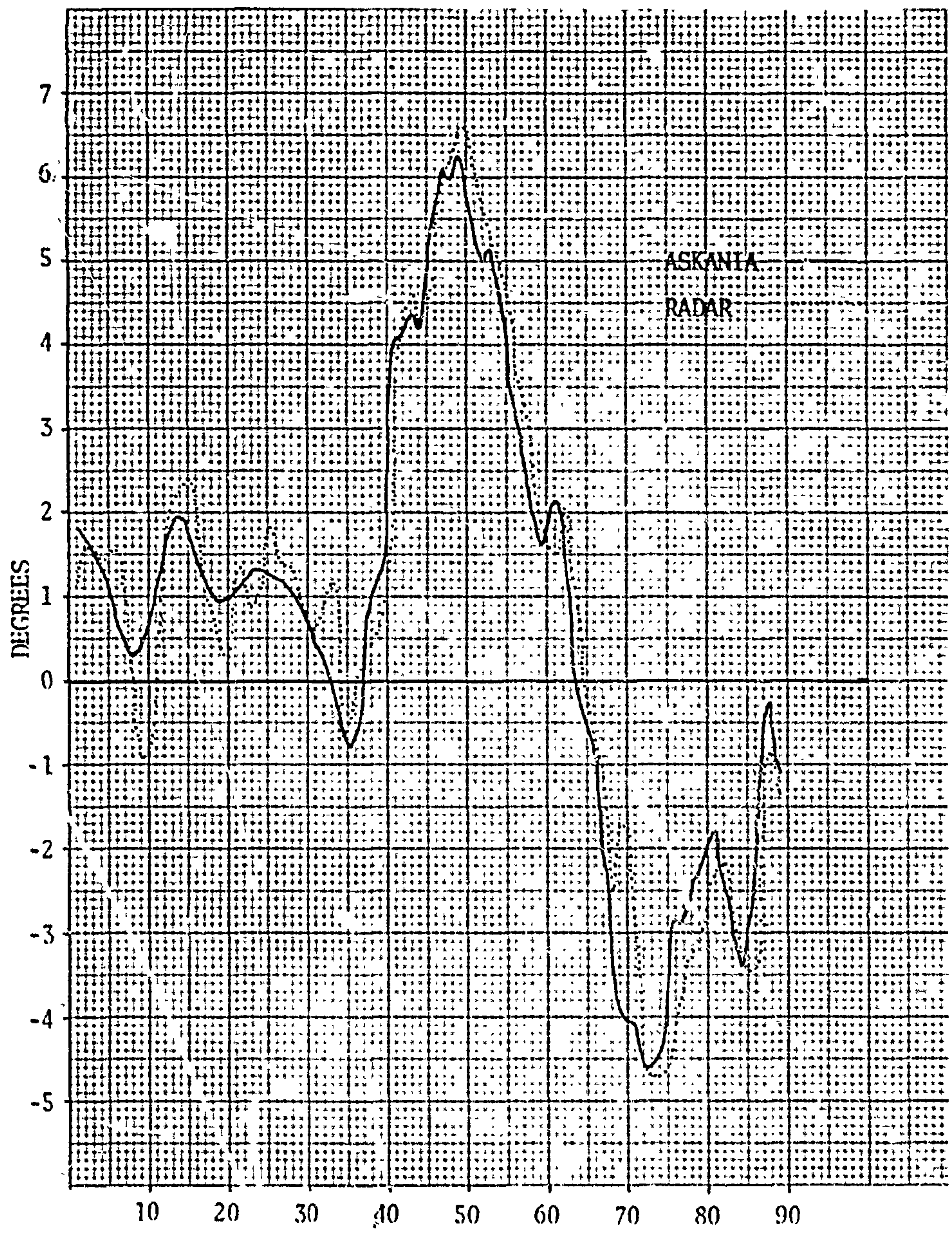


Figure 4 Flight 48–4, Velocity Vector Comparison

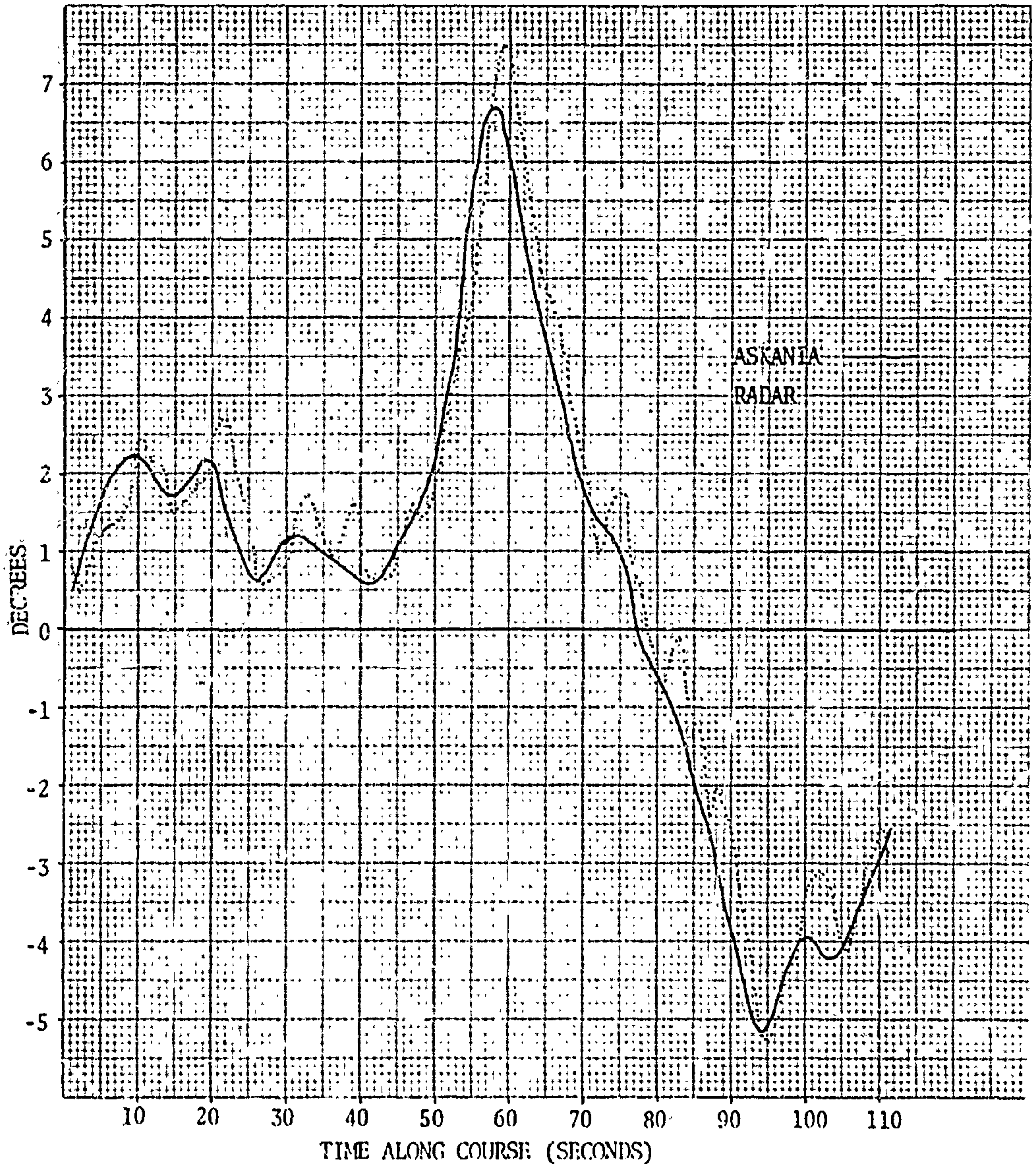


Figure 5 Flight 67–5, Velocity Vector Comparison

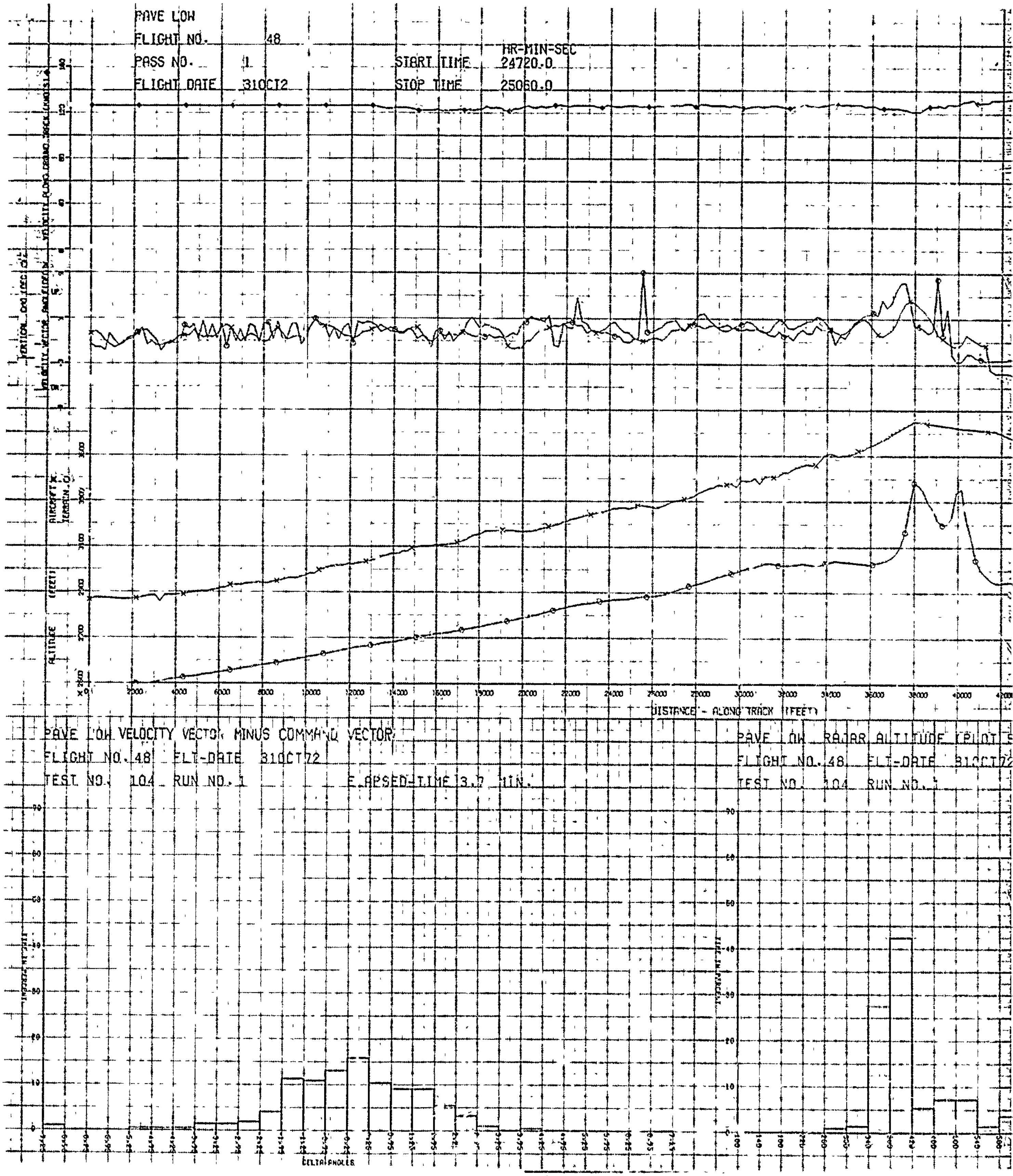
Table I

PAVE LOW INSTRUMENTATION PARAMETER LIST

Name	Range	Source
Event	Off-On	Switch
IRIG Timing	IRIG-E	Time Code Generator
Vertical Command	±27 degrees	APQ-141 Radar
Roll Angle	±20 degrees	Vertical Gyro
Horizontal Drift Angle	±36 degrees	Doppler Radar
Pitch Angle	±27 degrees	Vertical Gyro
Pressure Altitude	0-10180	Walso-Leonard Pressure Transducer
Laser Altitude	0-1,000 feet	TFRIS Pod
Radar Altitude	0-2,000 feet	Radar Altimeter
Lateral Stick Position	Full Left-Right	Position Transducer
Vertical Velocity Vector	±27 degrees	APQ-141 Radar
Longitudinal Stick Position	Full Aft-Fwd	Position Transducer
Velocity Along Ground Track	0-166 knots	Doppler Radar
Vertical Acceleration	-2 to +4 g's	Vertical Accelerometer
Vertical Velocity	±3012 fps	Doppler Radar
28 vdc Monitor	23.78-36.59 volts	APQ-141 Radar
Collective Stick Position	Full Down-Up	Position Transducer
AC Power Monitor		APQ-141 Radar

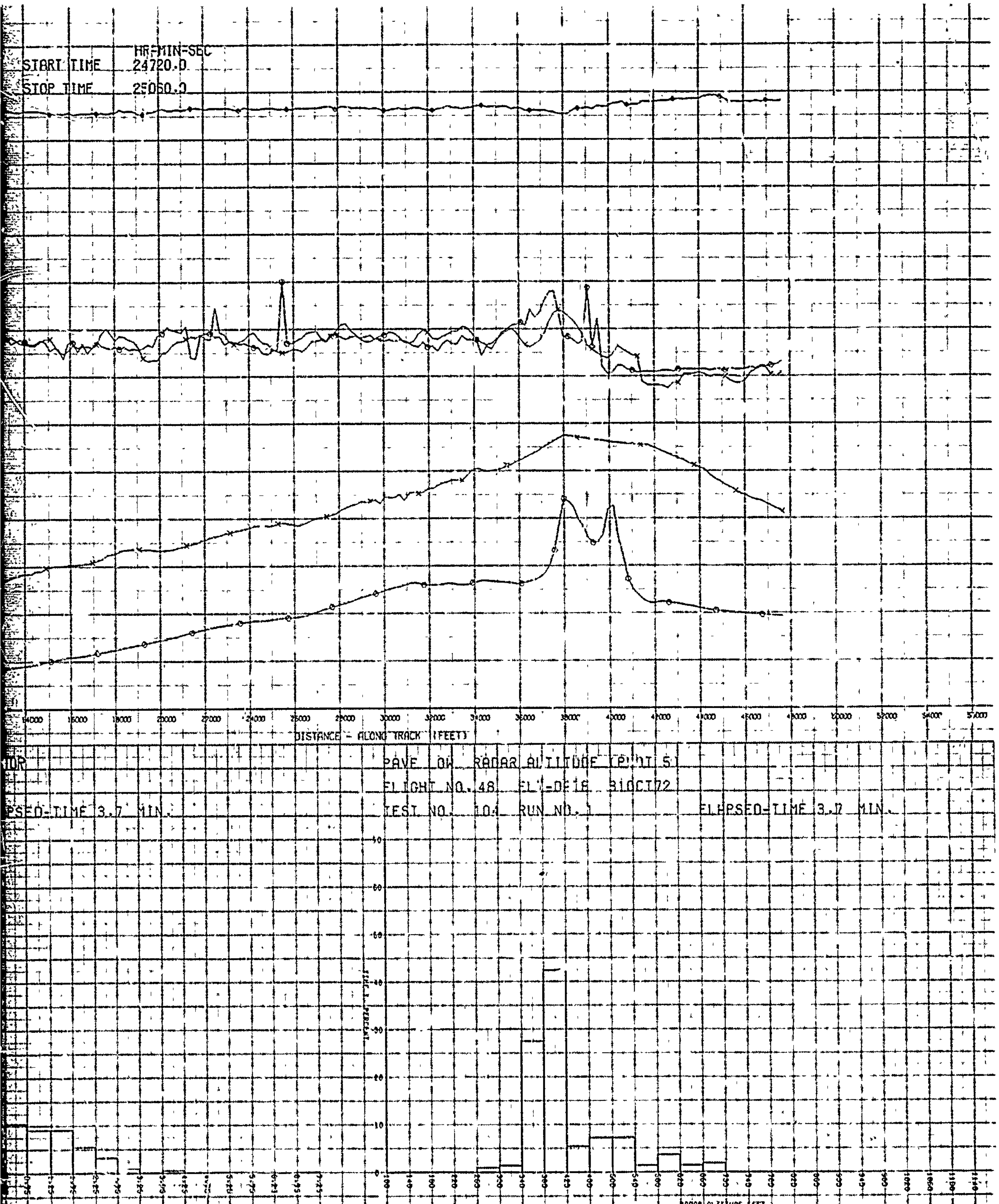
APPENDIX III
DATA

Figures 1 through 55



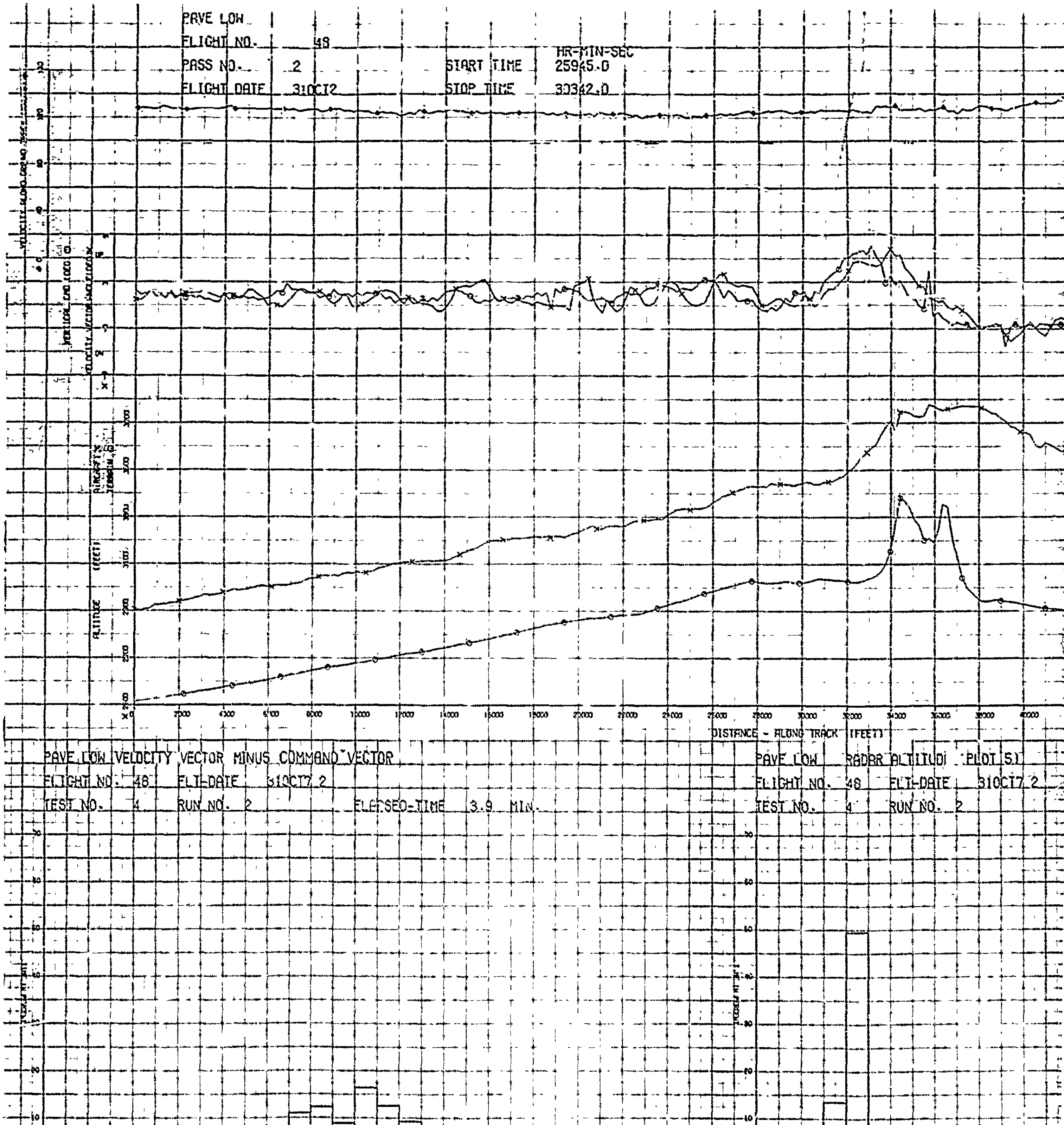
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 1



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 1



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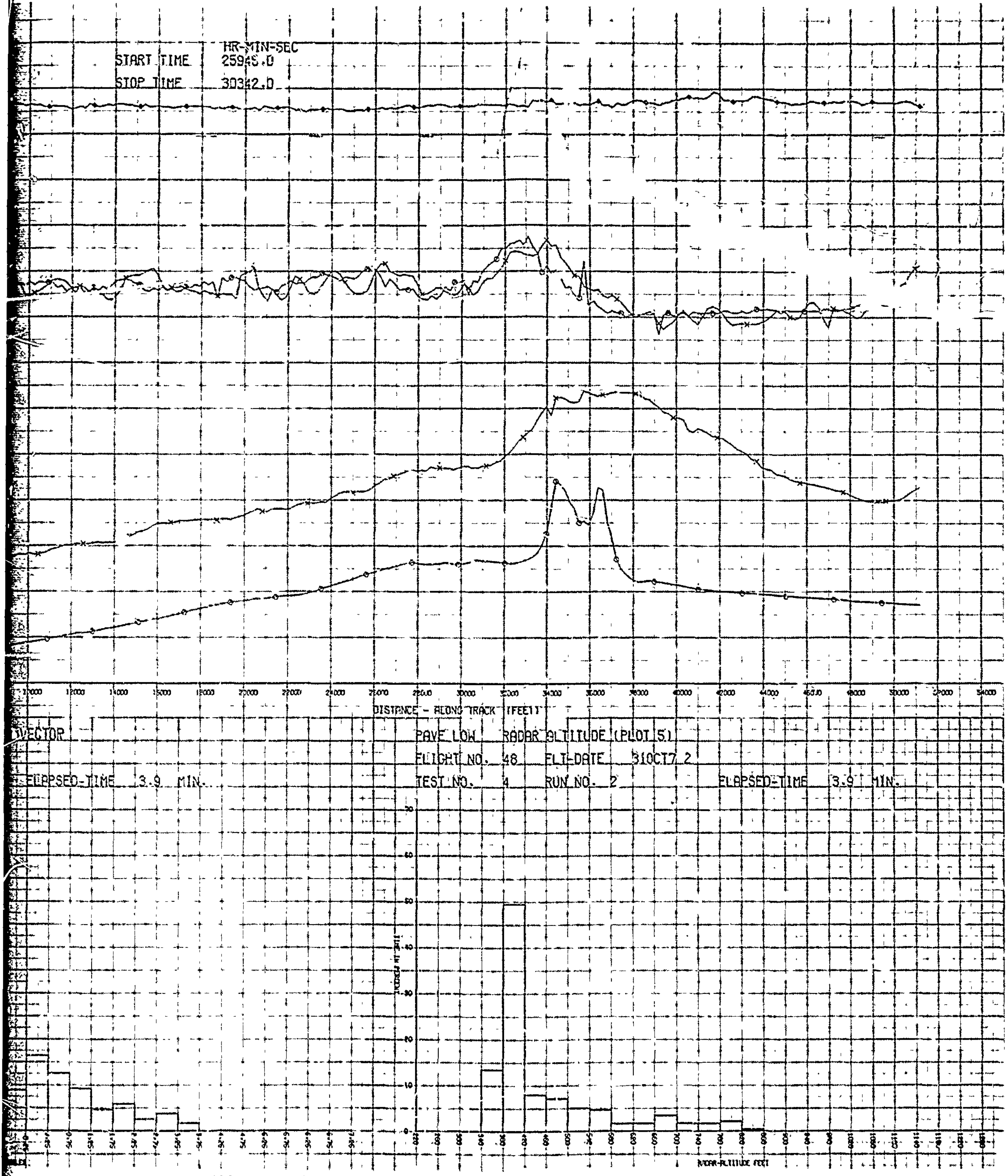
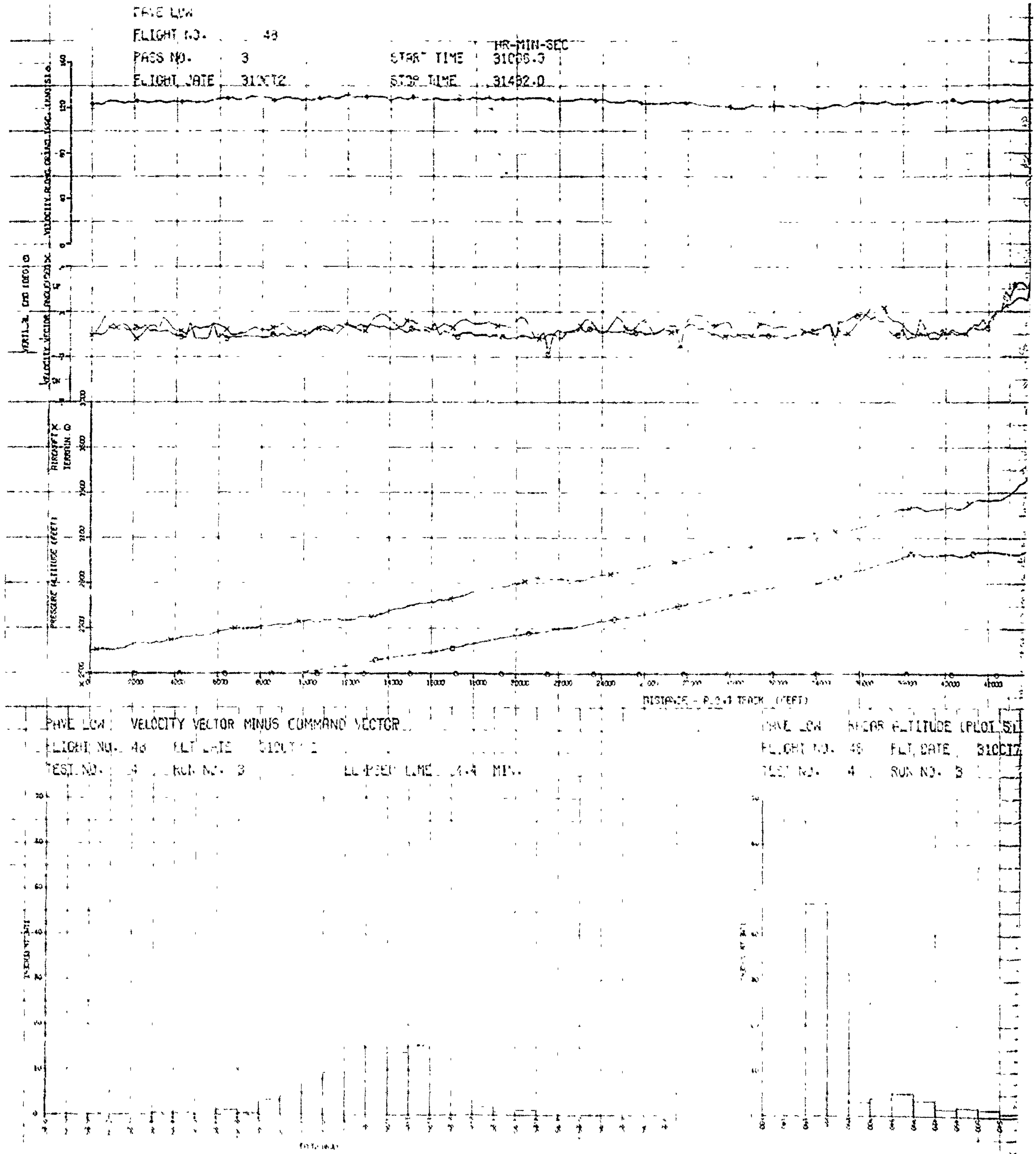
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 2



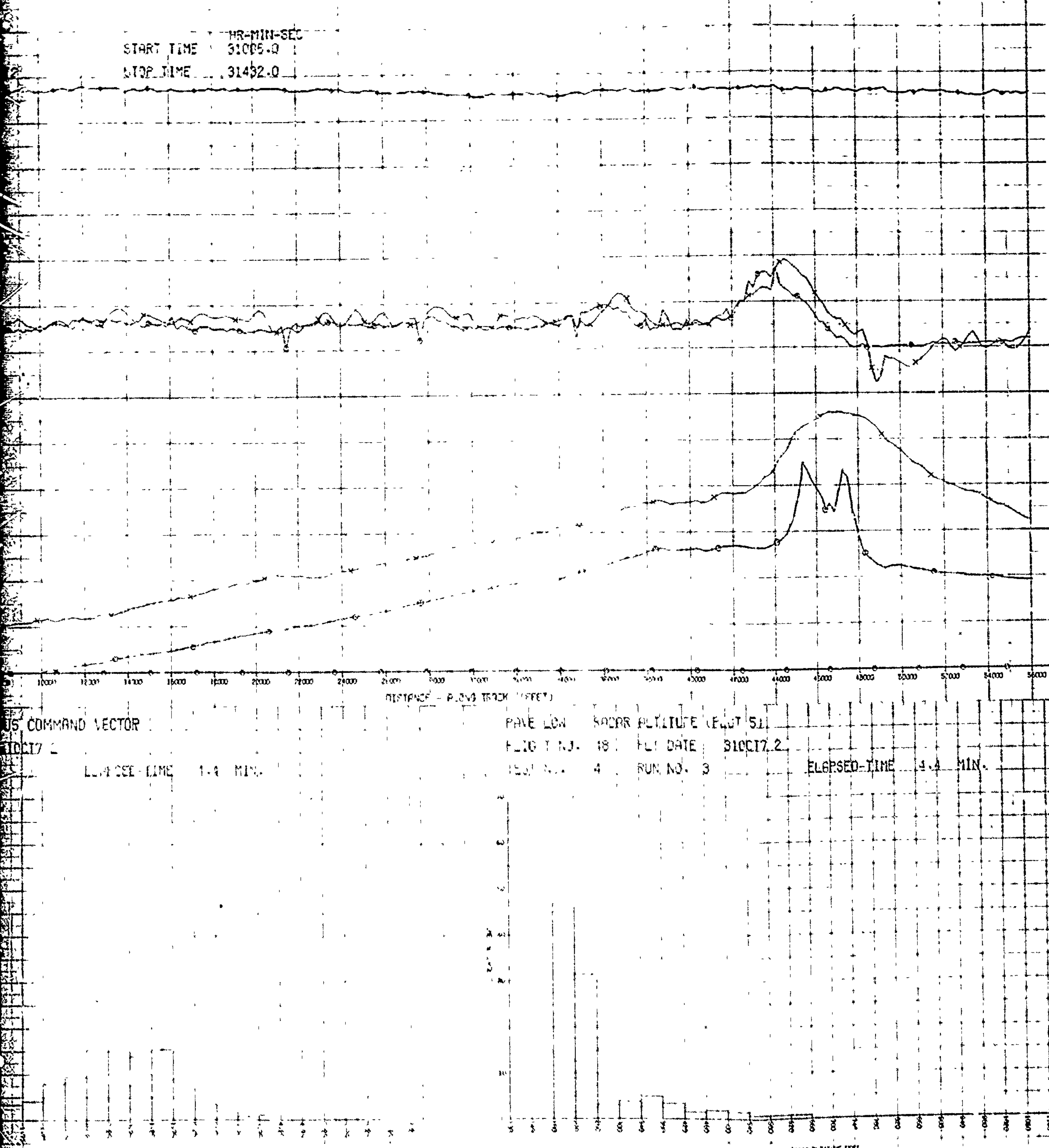
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 2



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

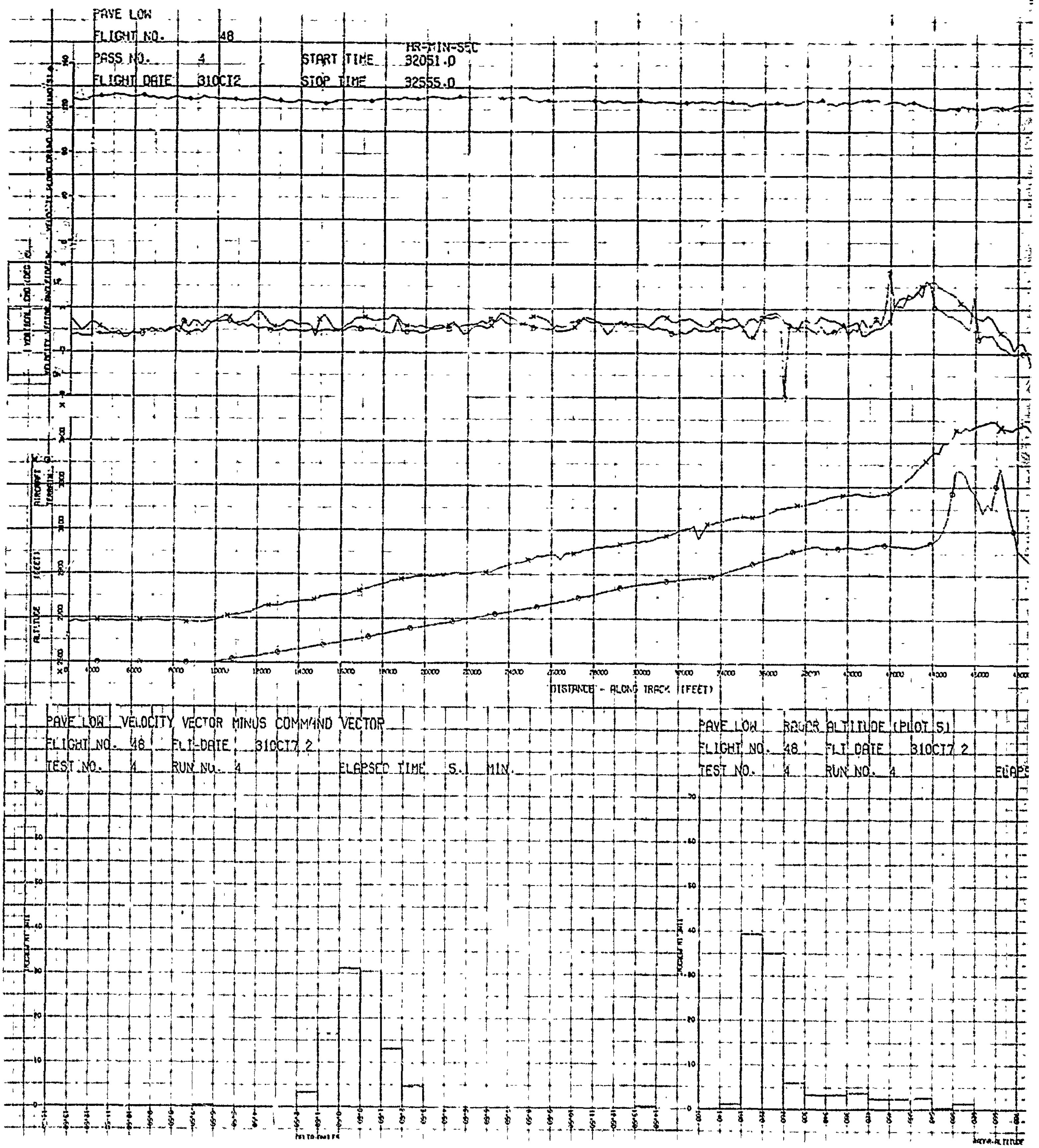
FIGURE 3



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

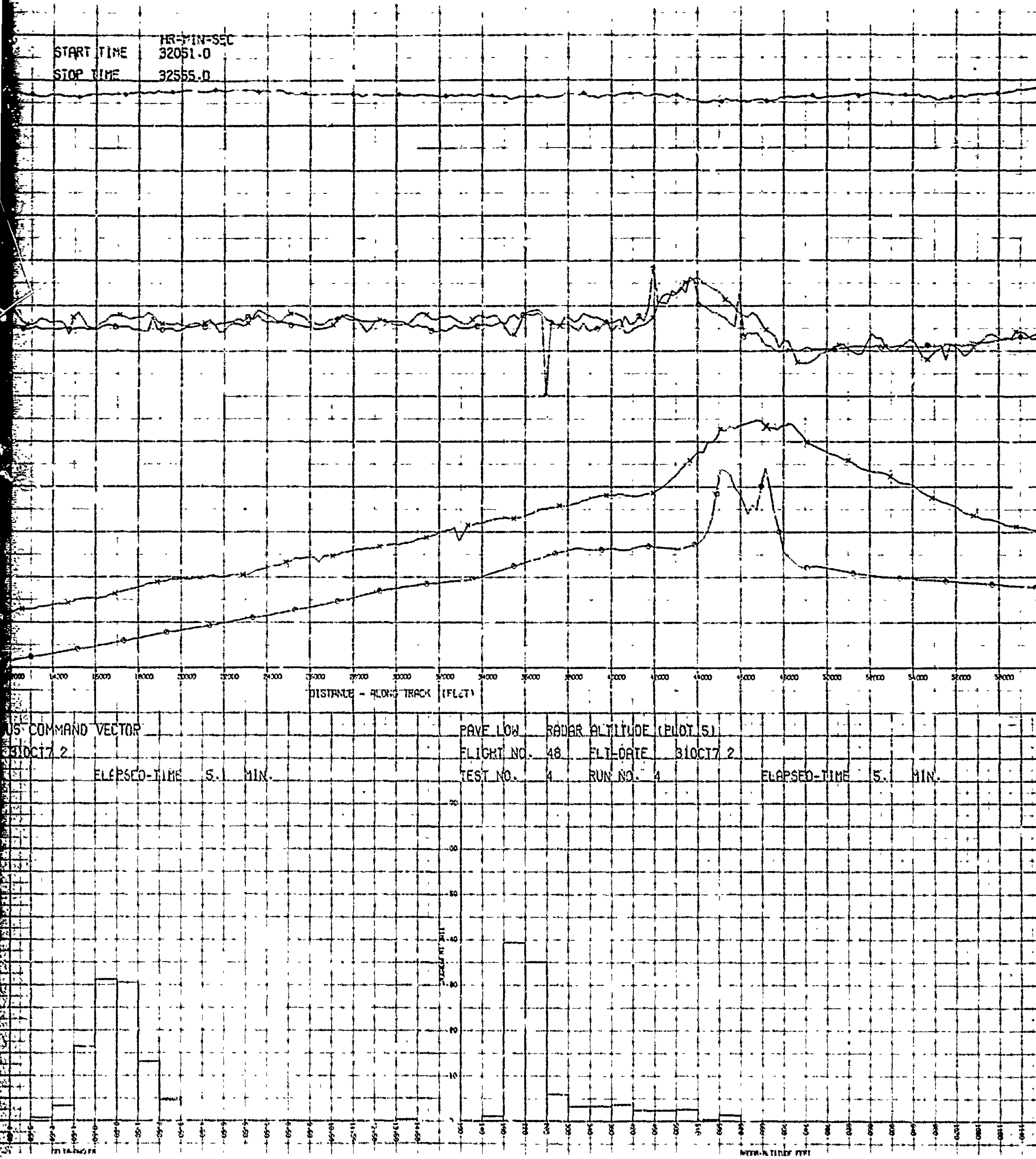
FIGURE 3

2



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

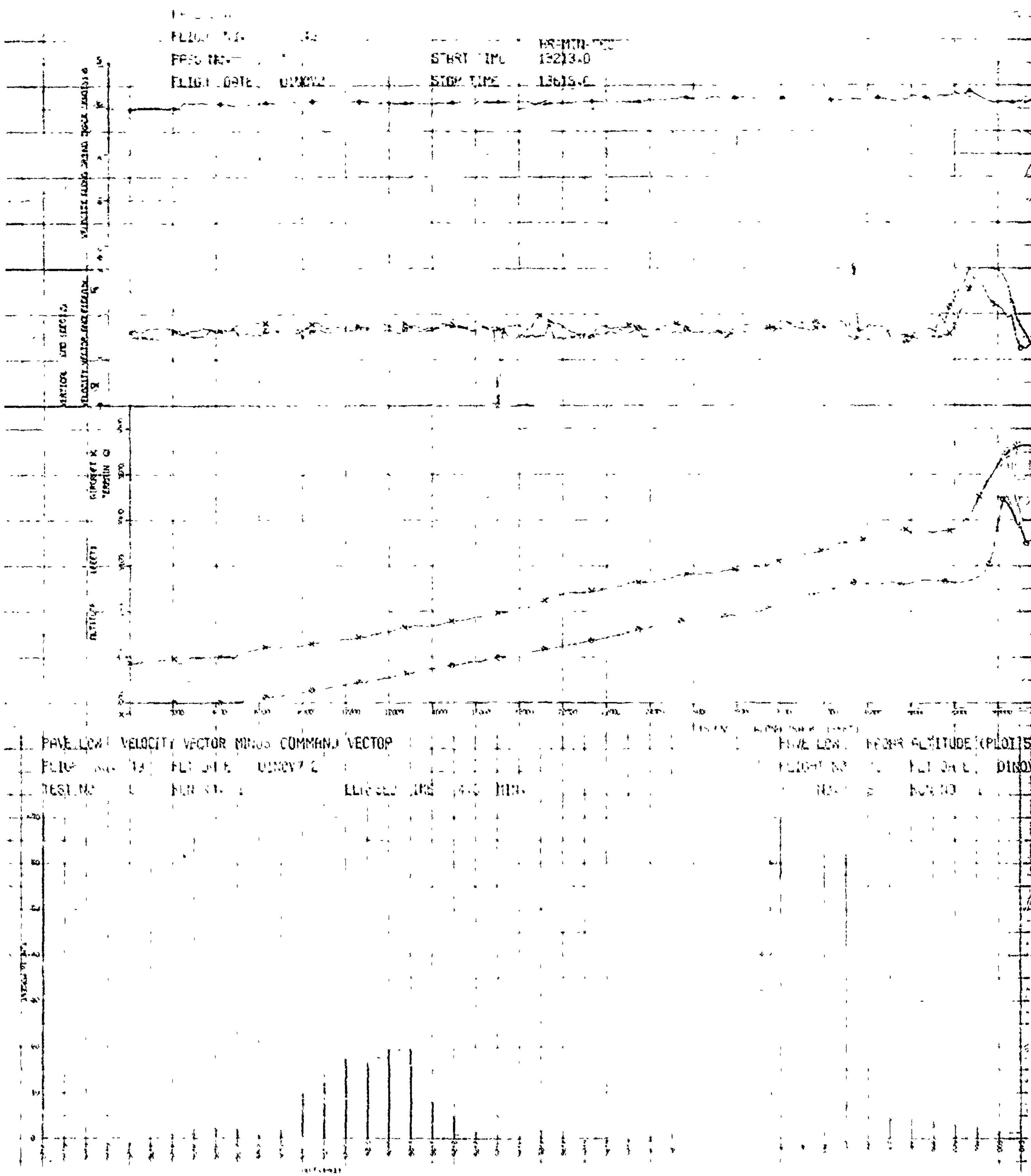
FIGURE 4



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

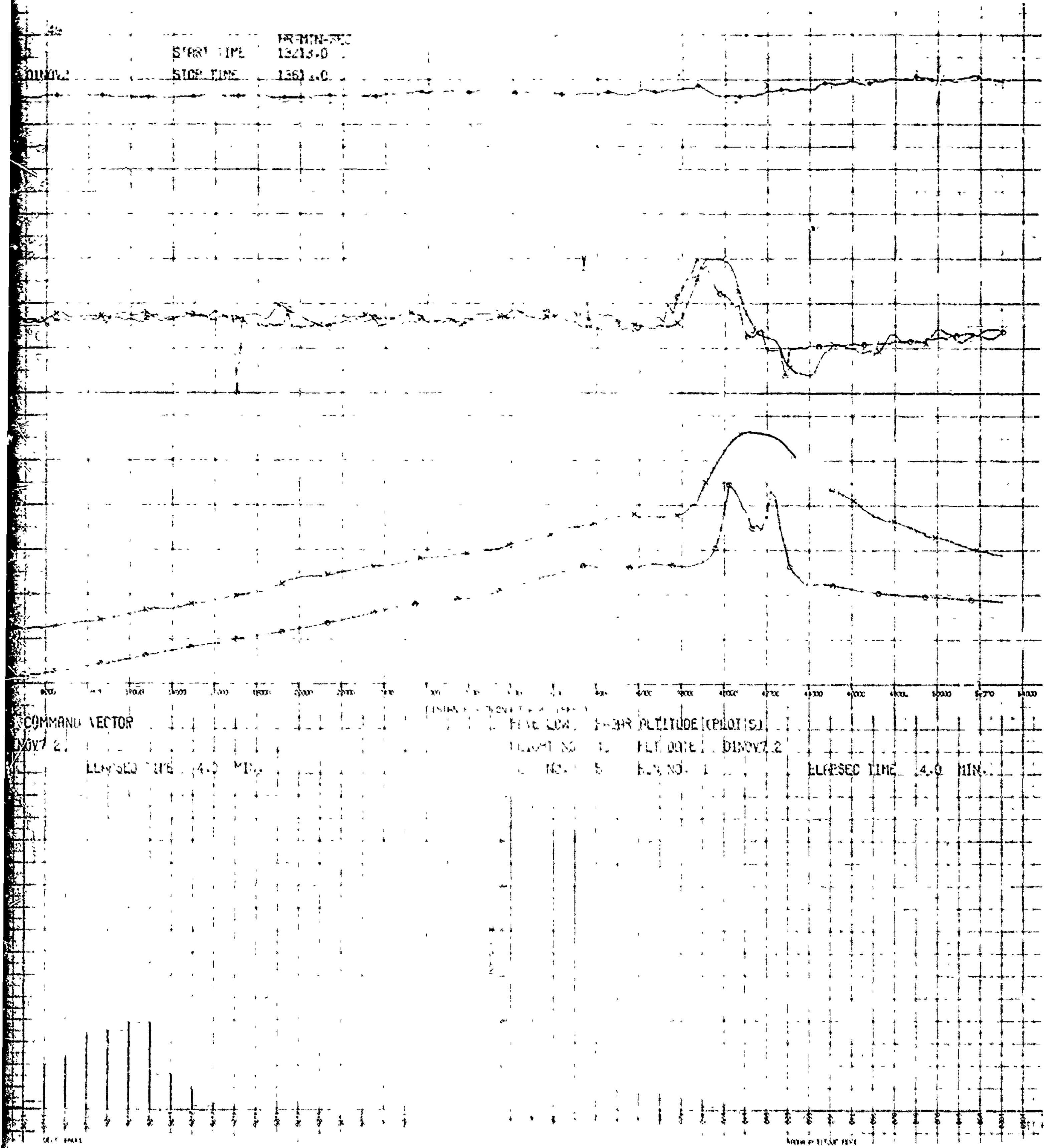
FIGURE 4

2



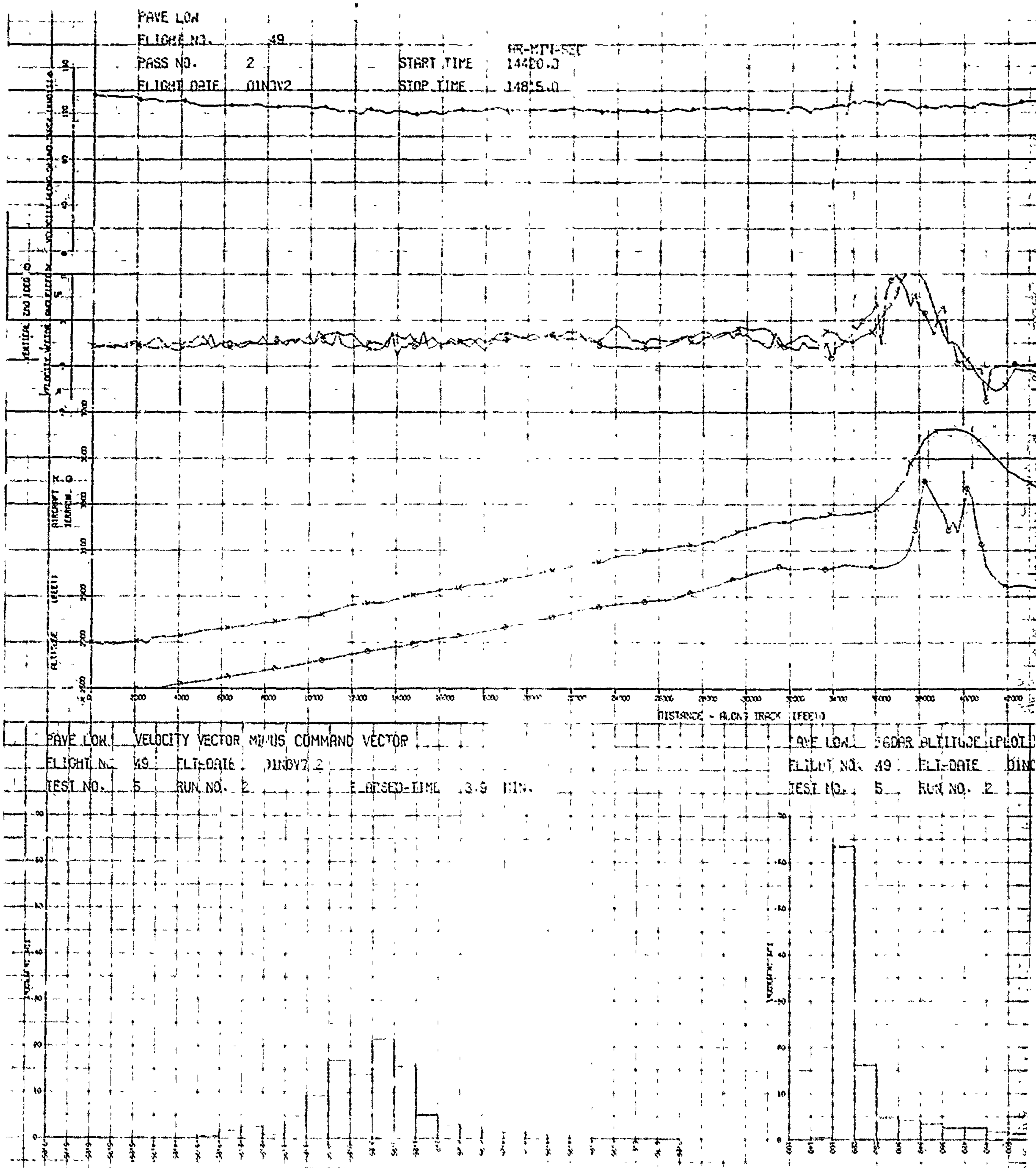
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 5



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 5



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 6

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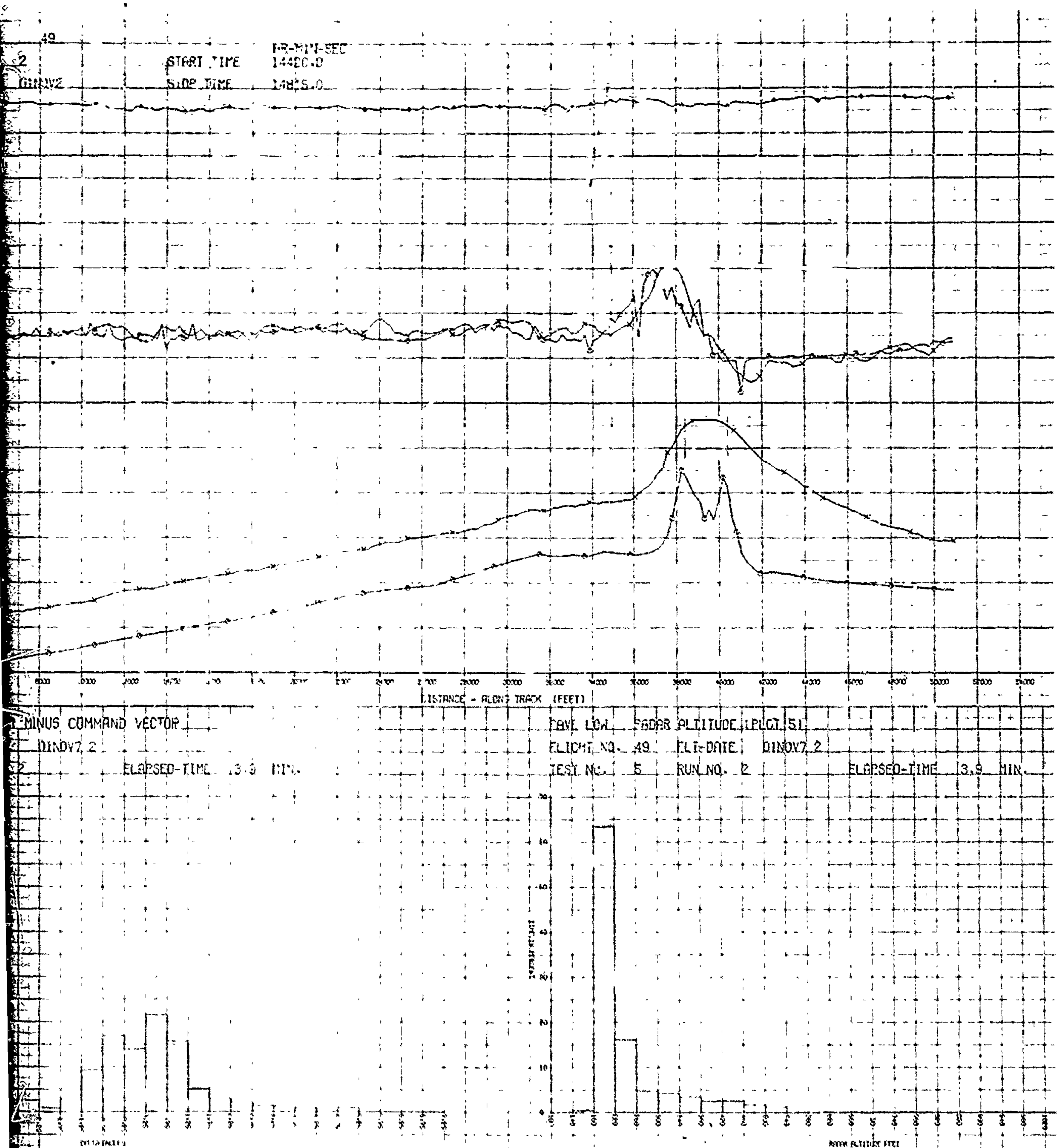

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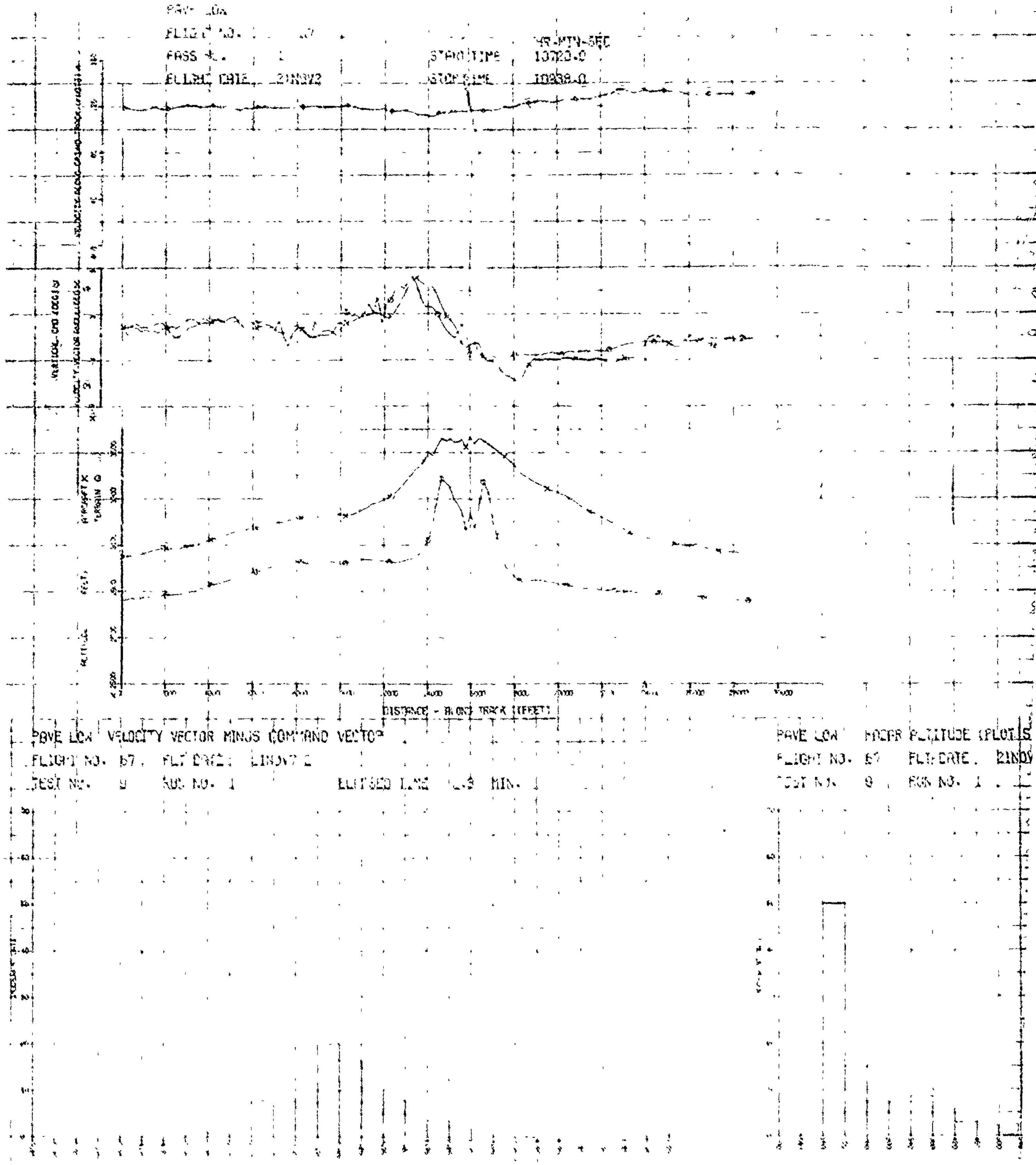
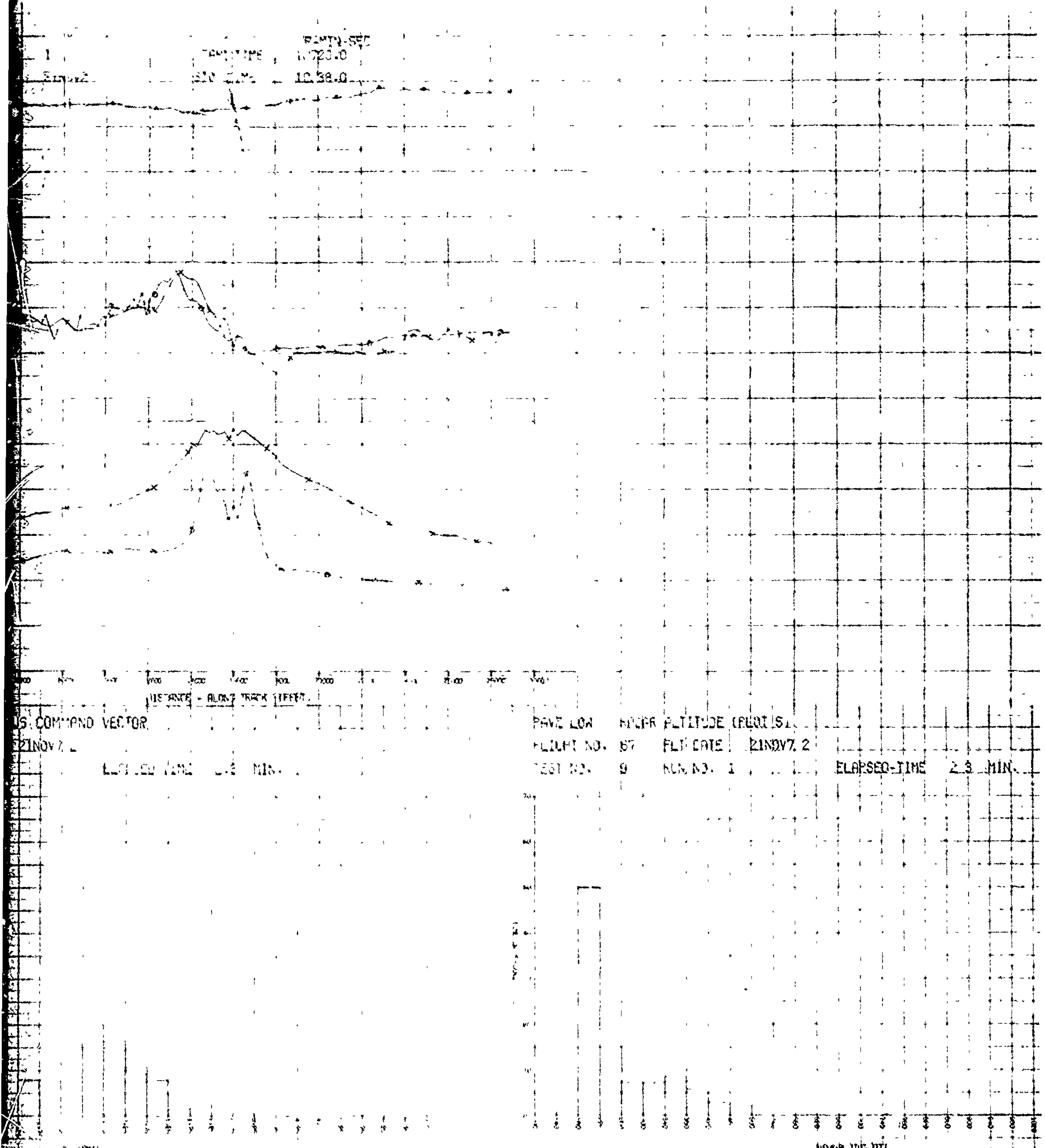
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 6



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

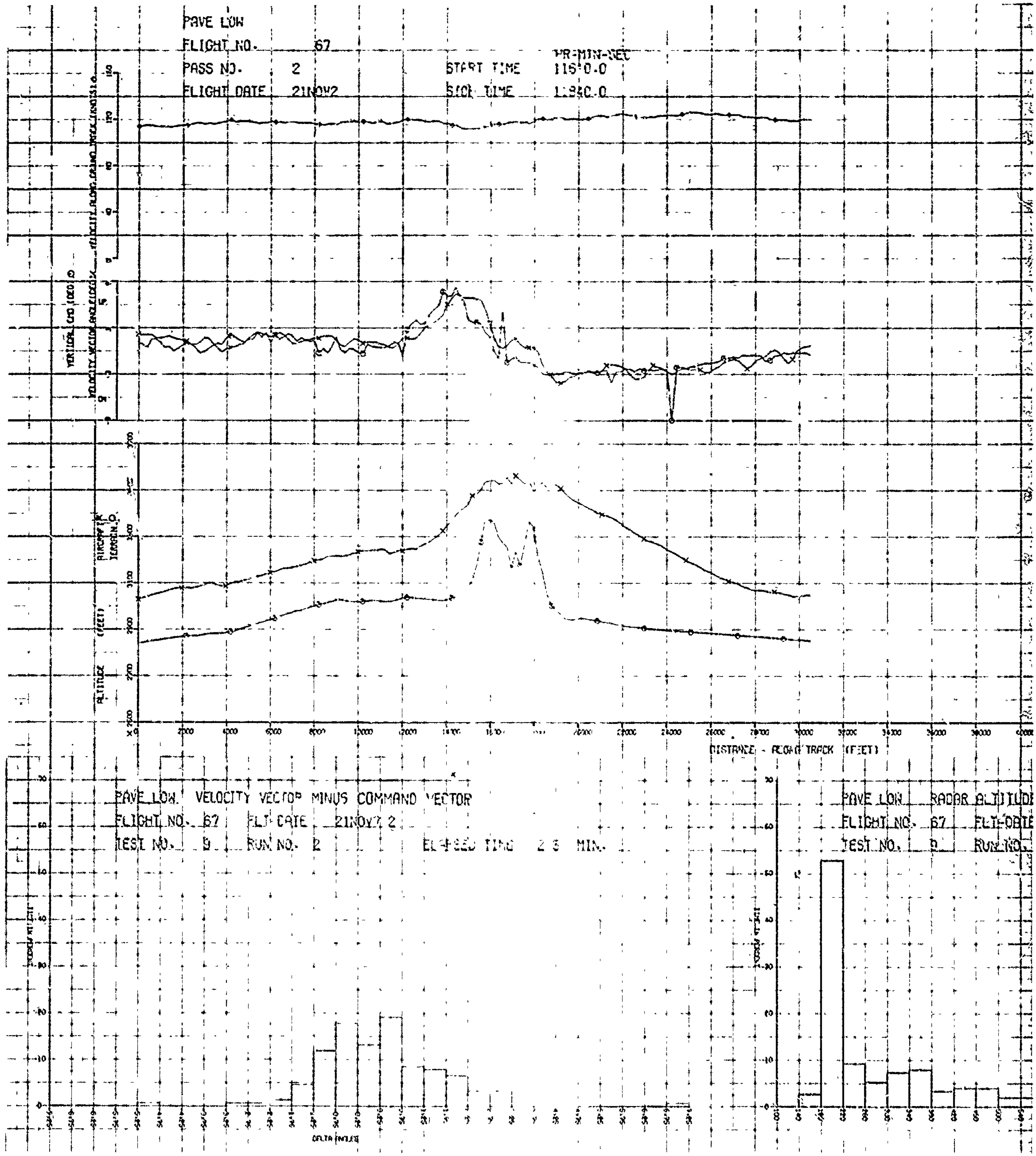
FIGURE 7



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

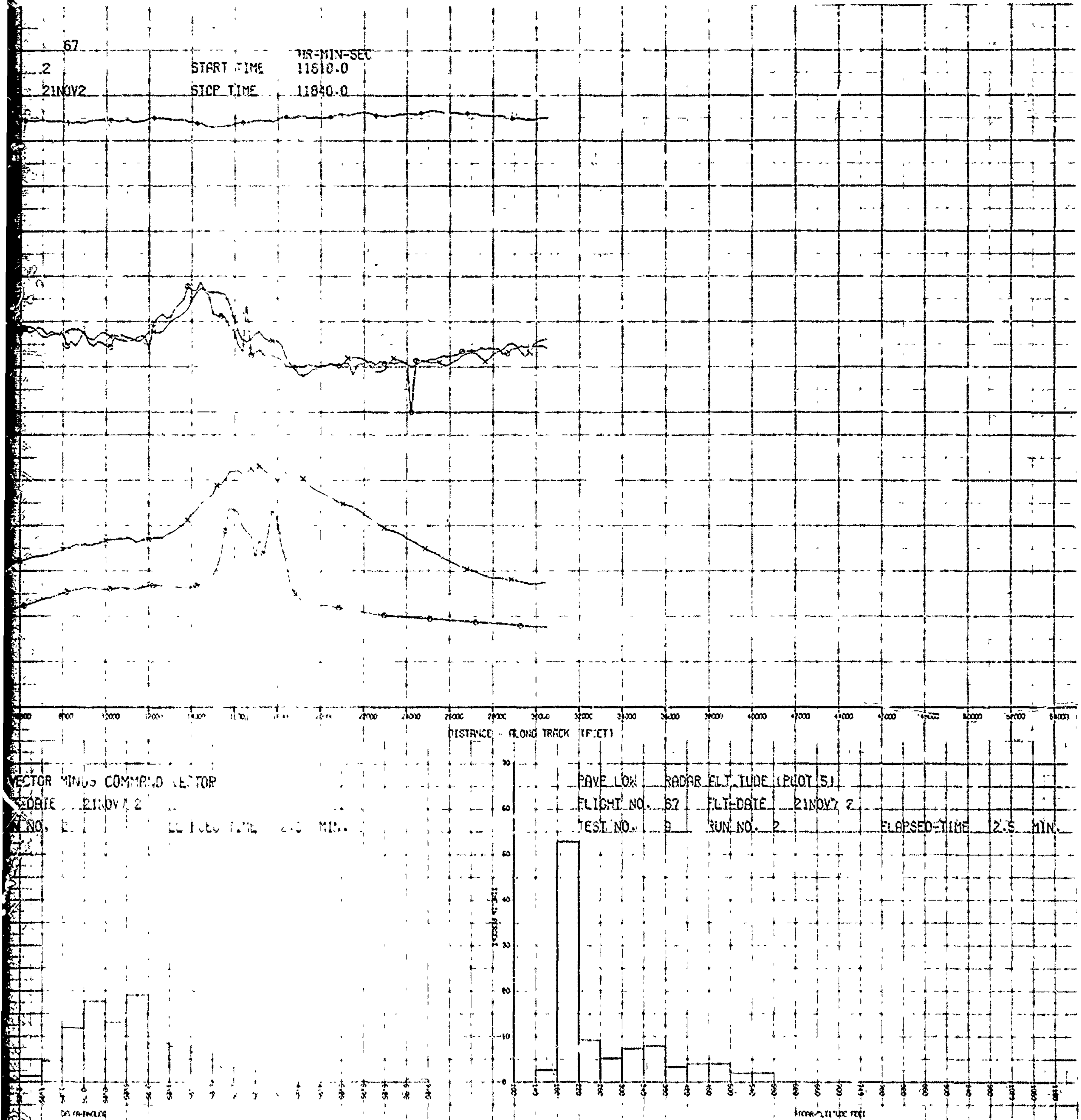
FIGURE 7

2



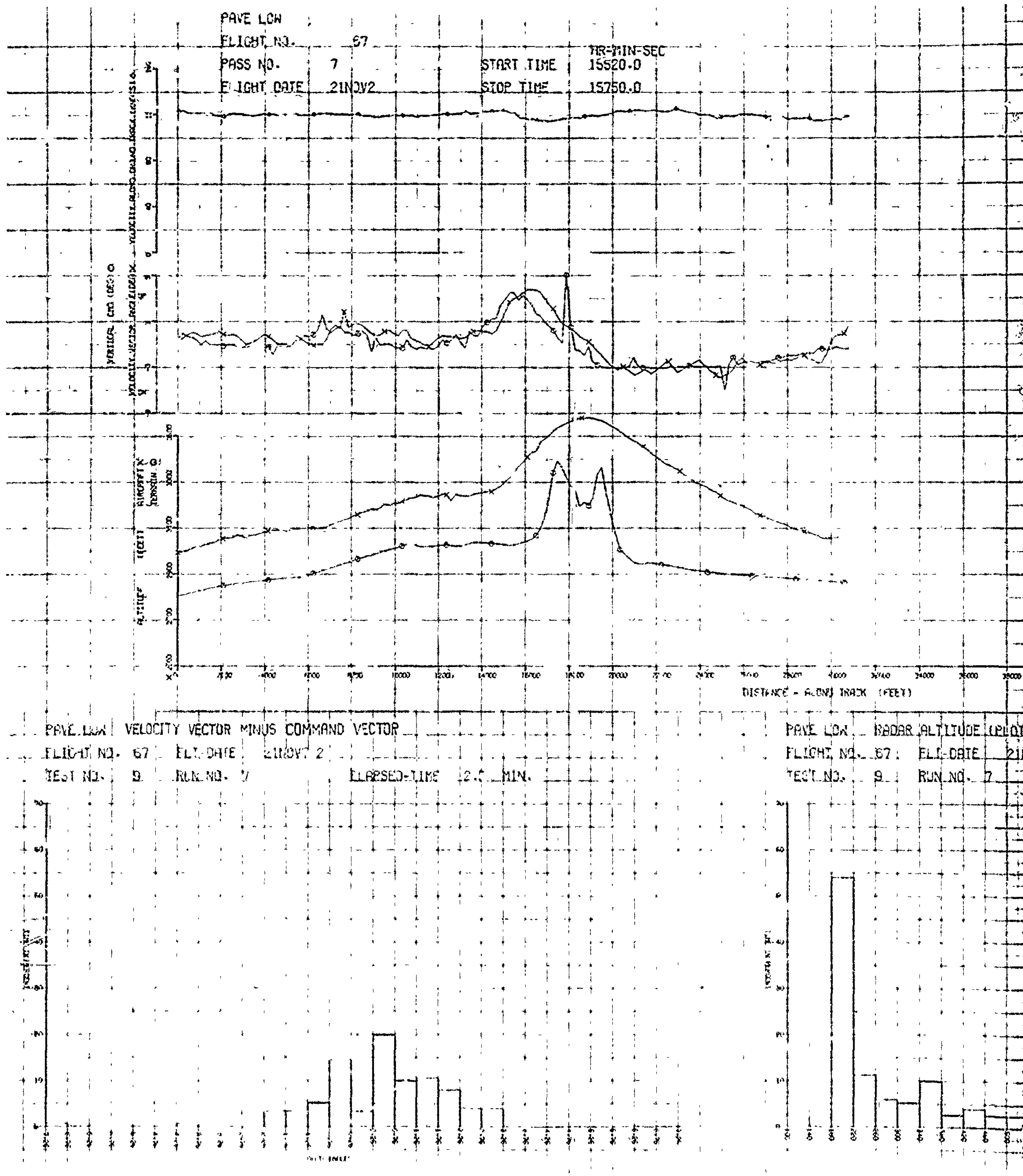
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 8



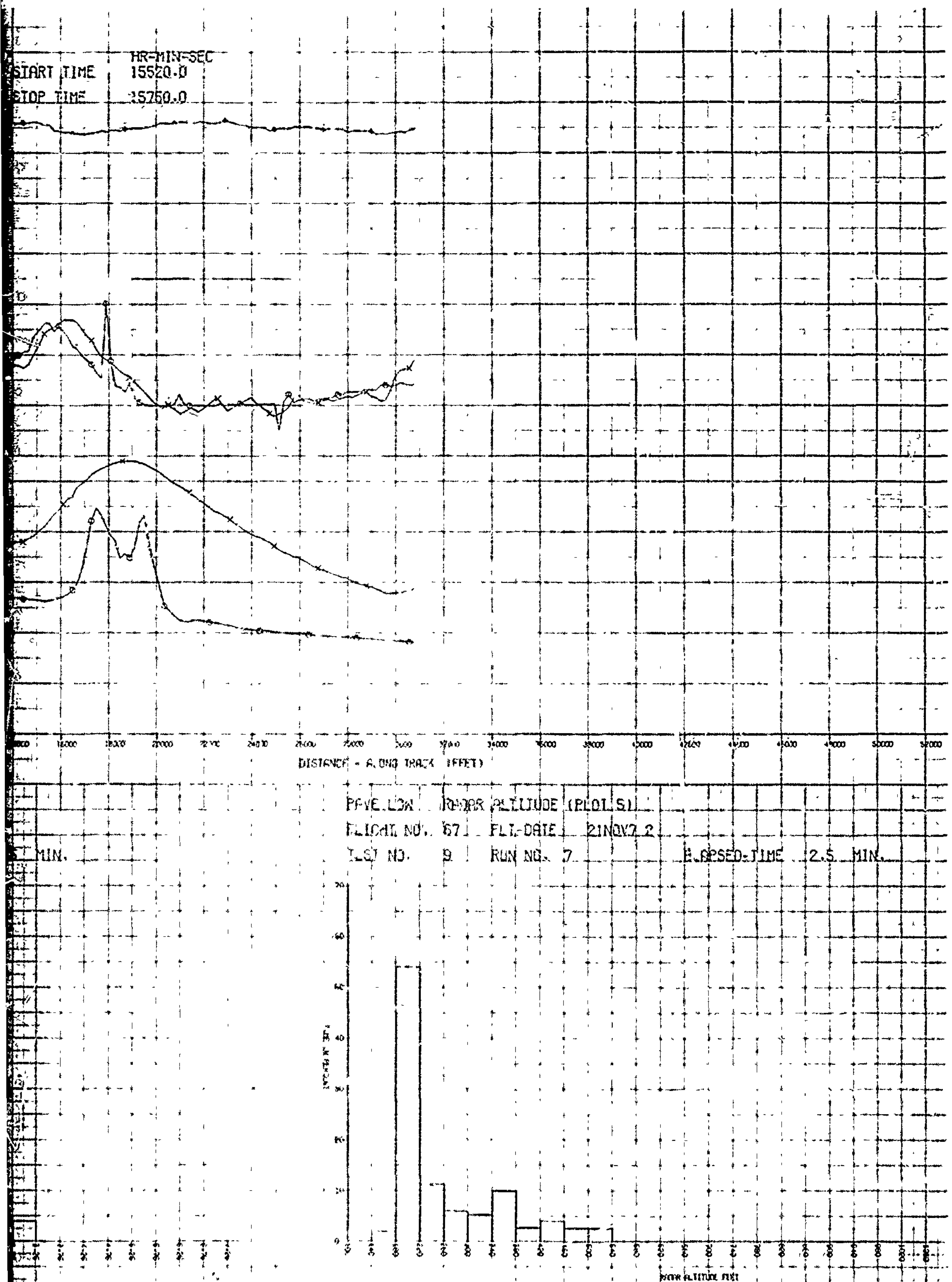
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 8



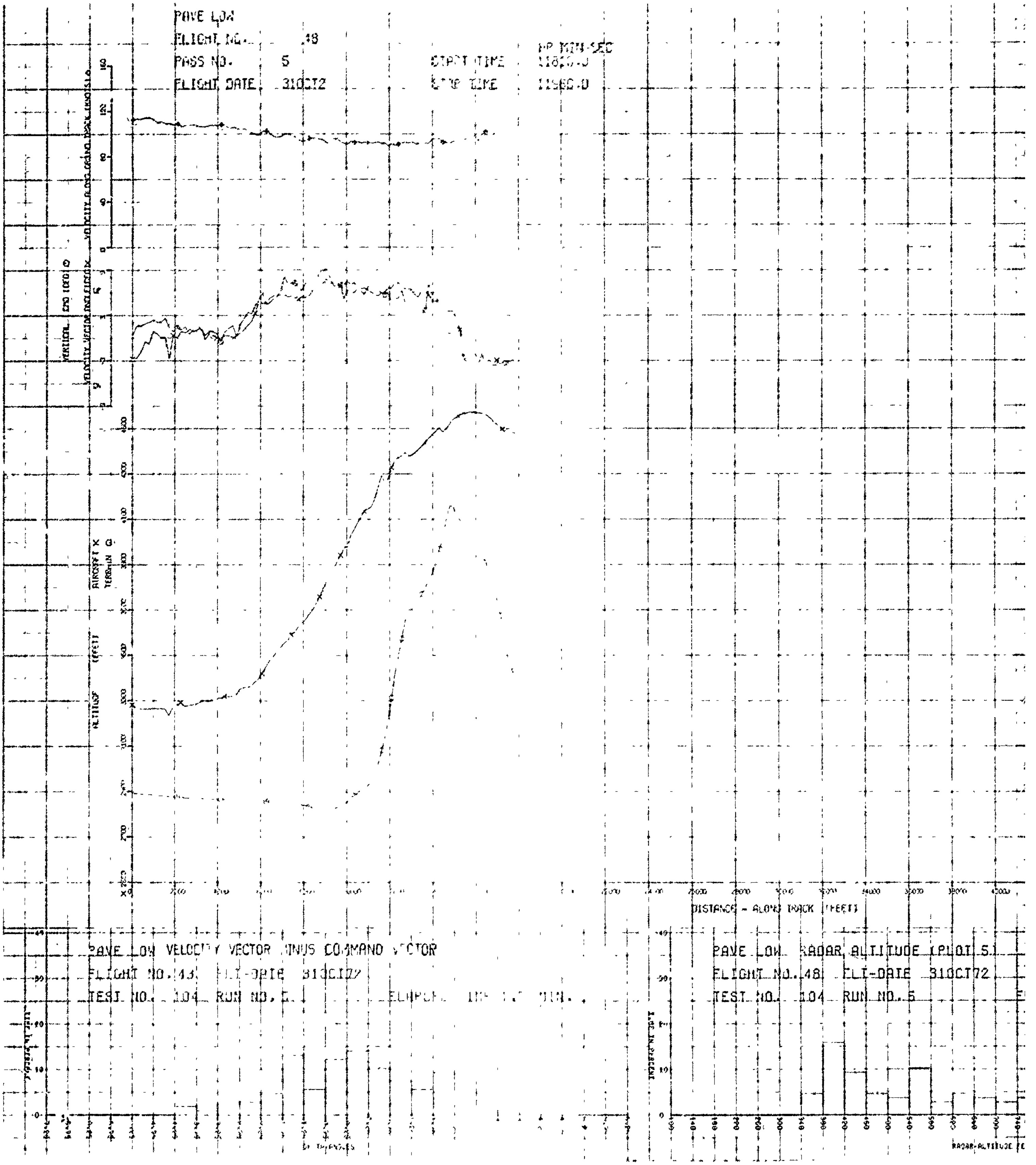
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 9



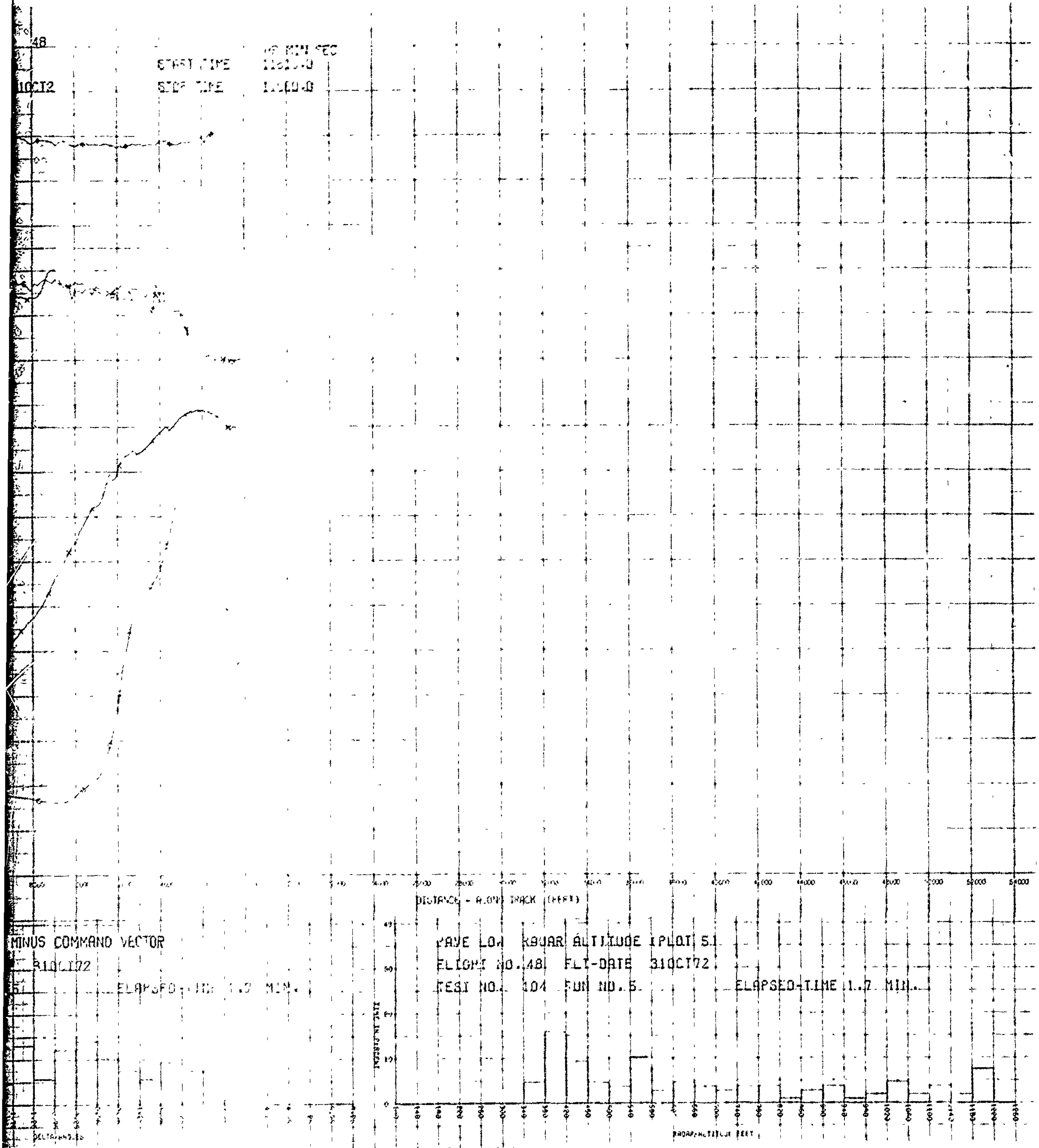
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 9



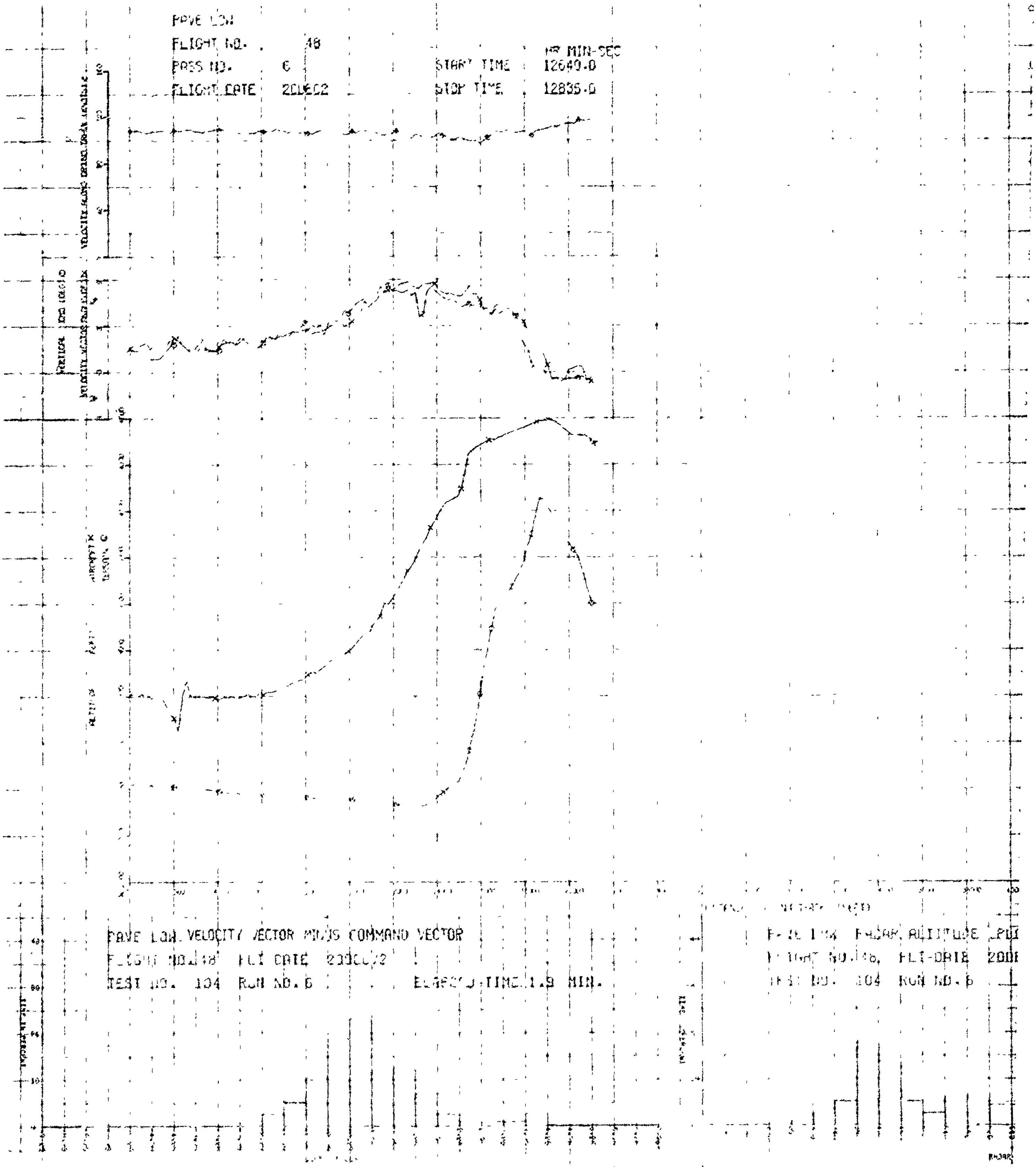
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 10



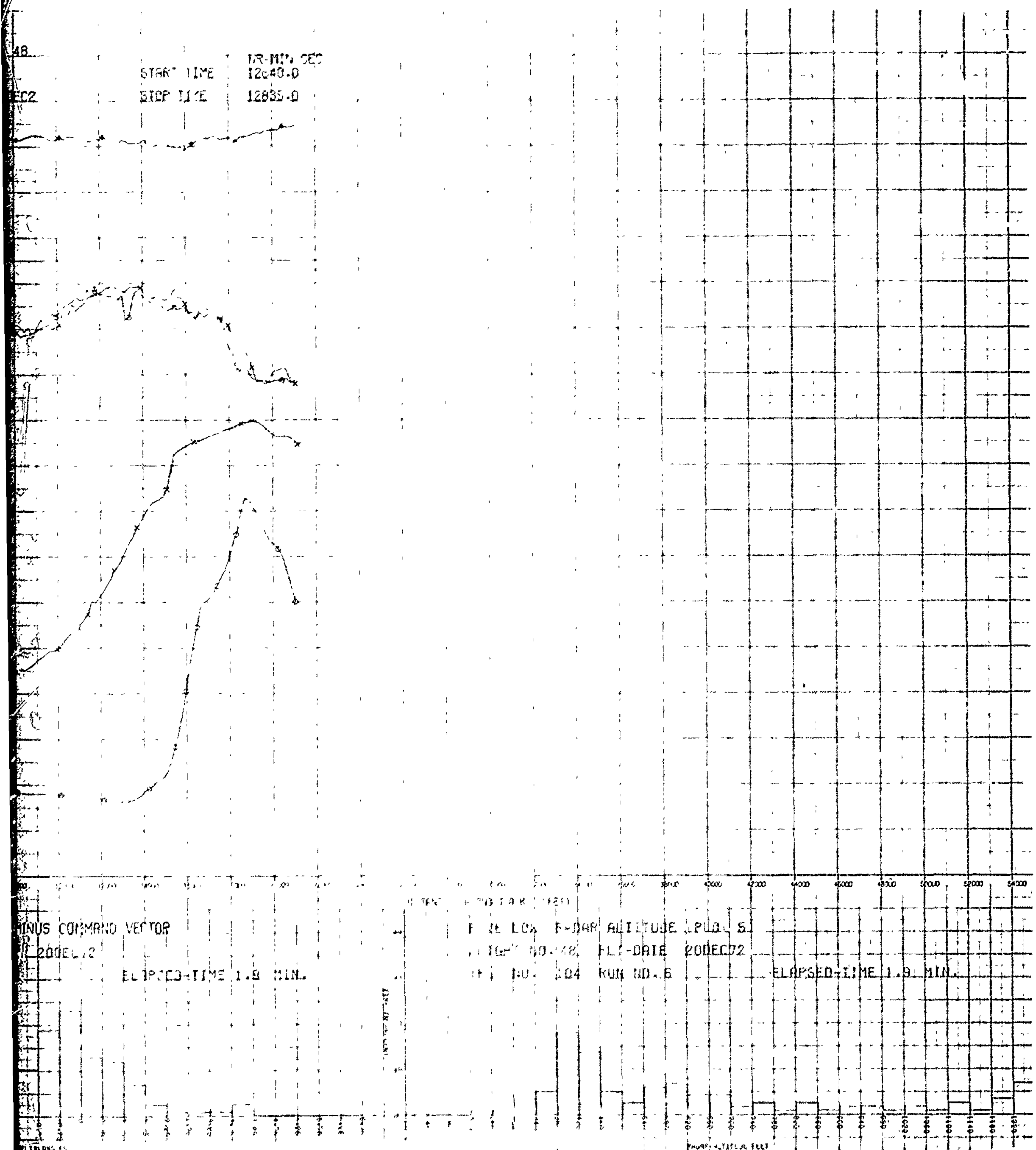
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 10



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

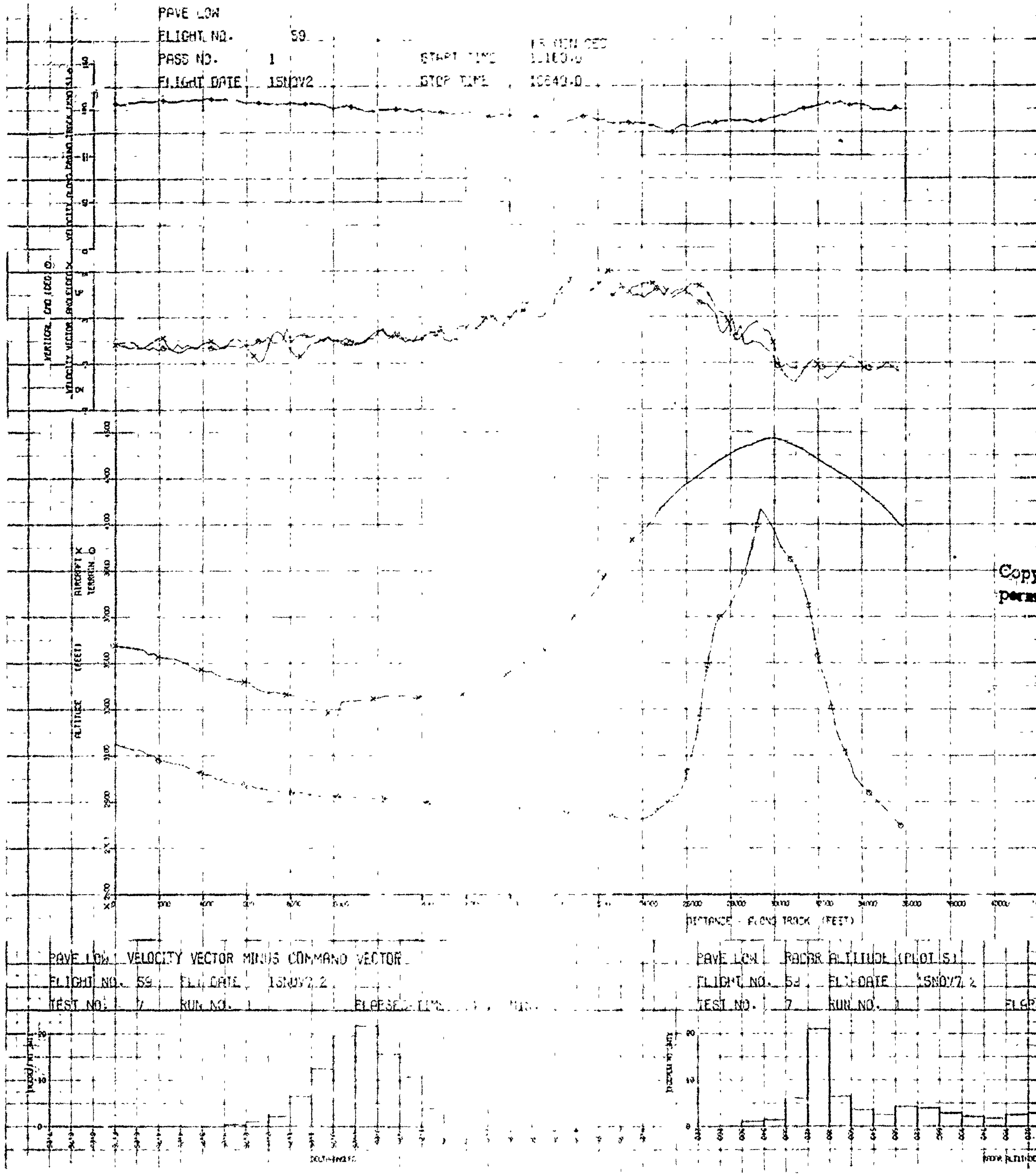
FIGURE 11



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

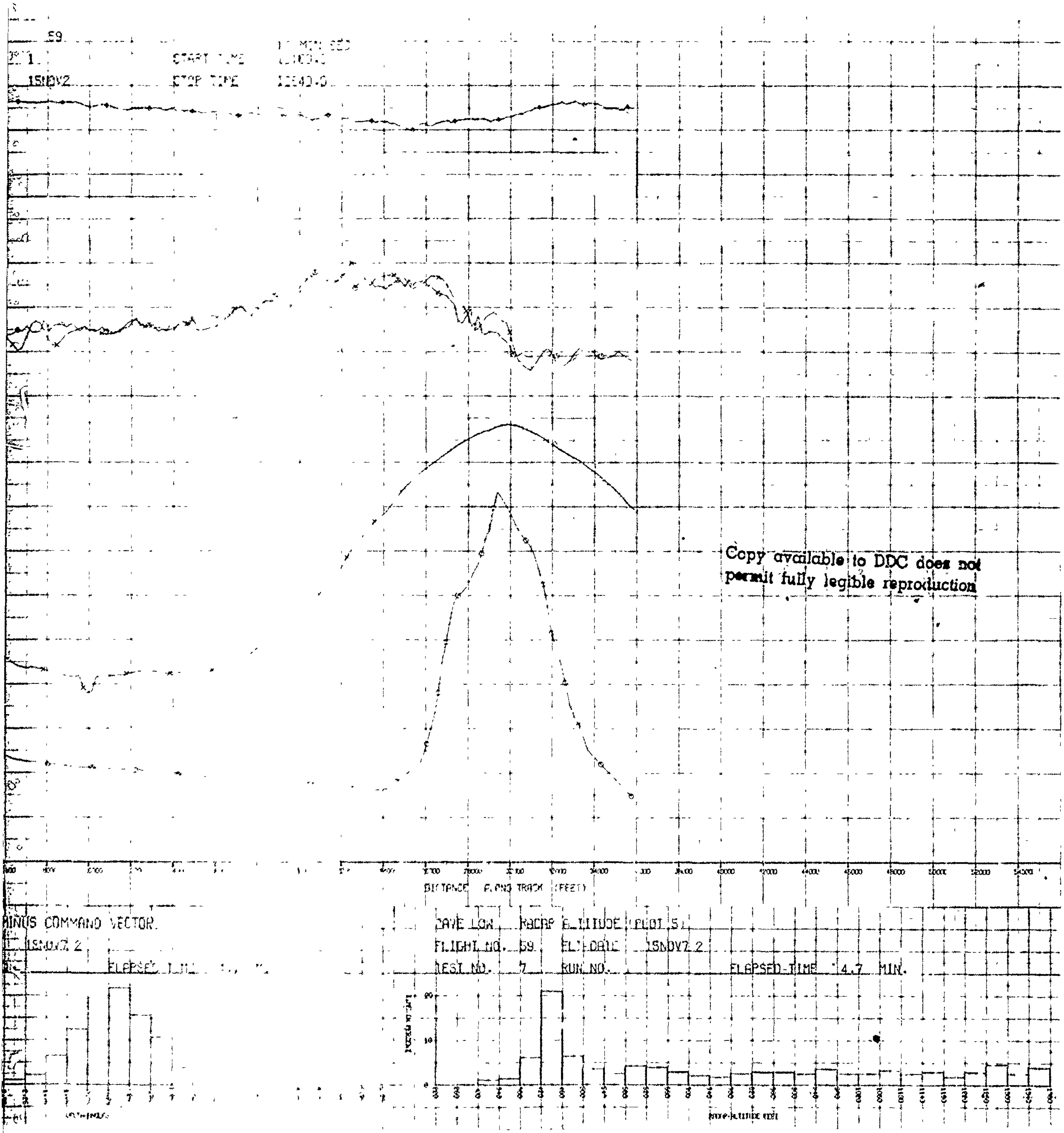
FIGURE 11

2



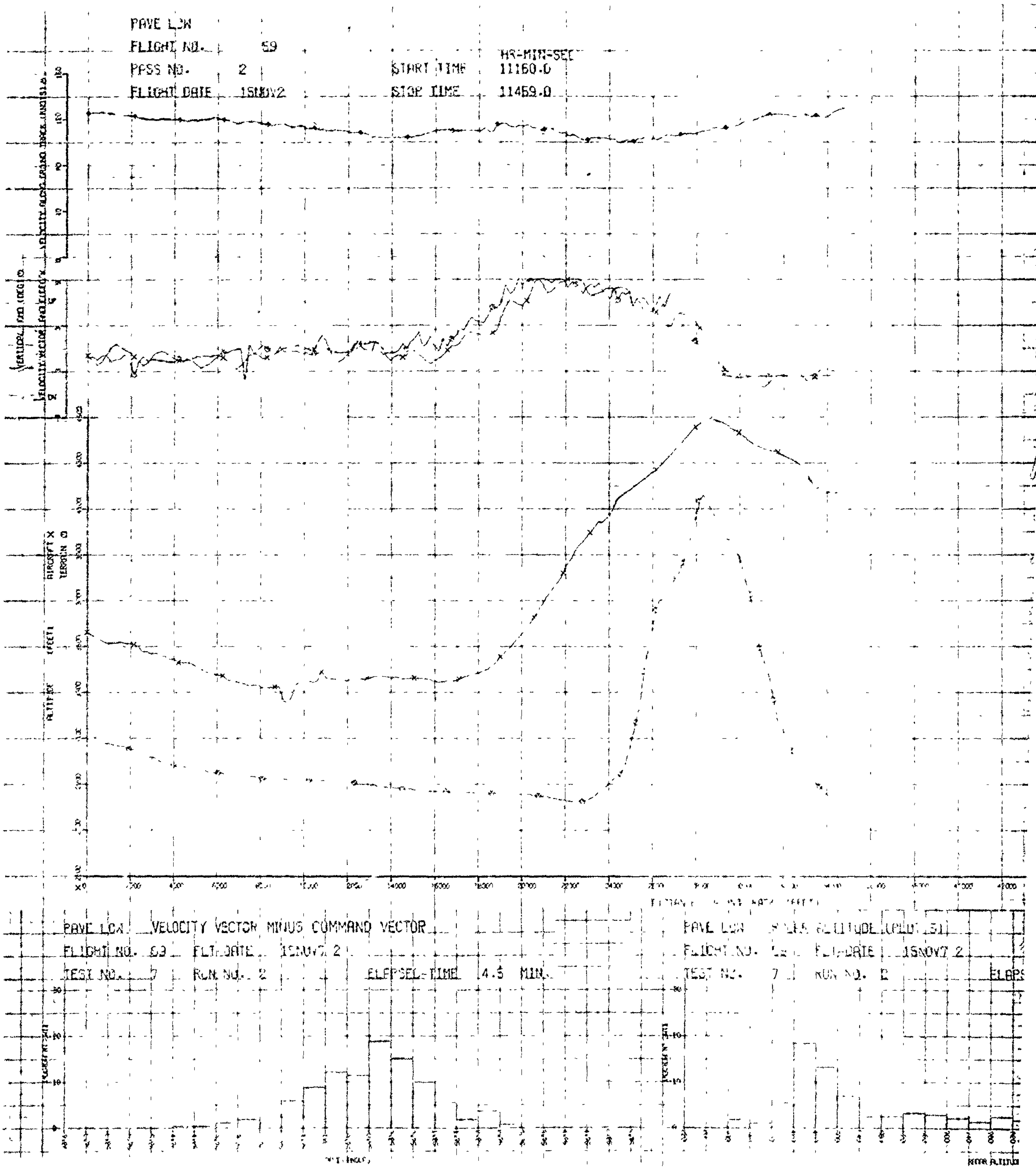
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 12



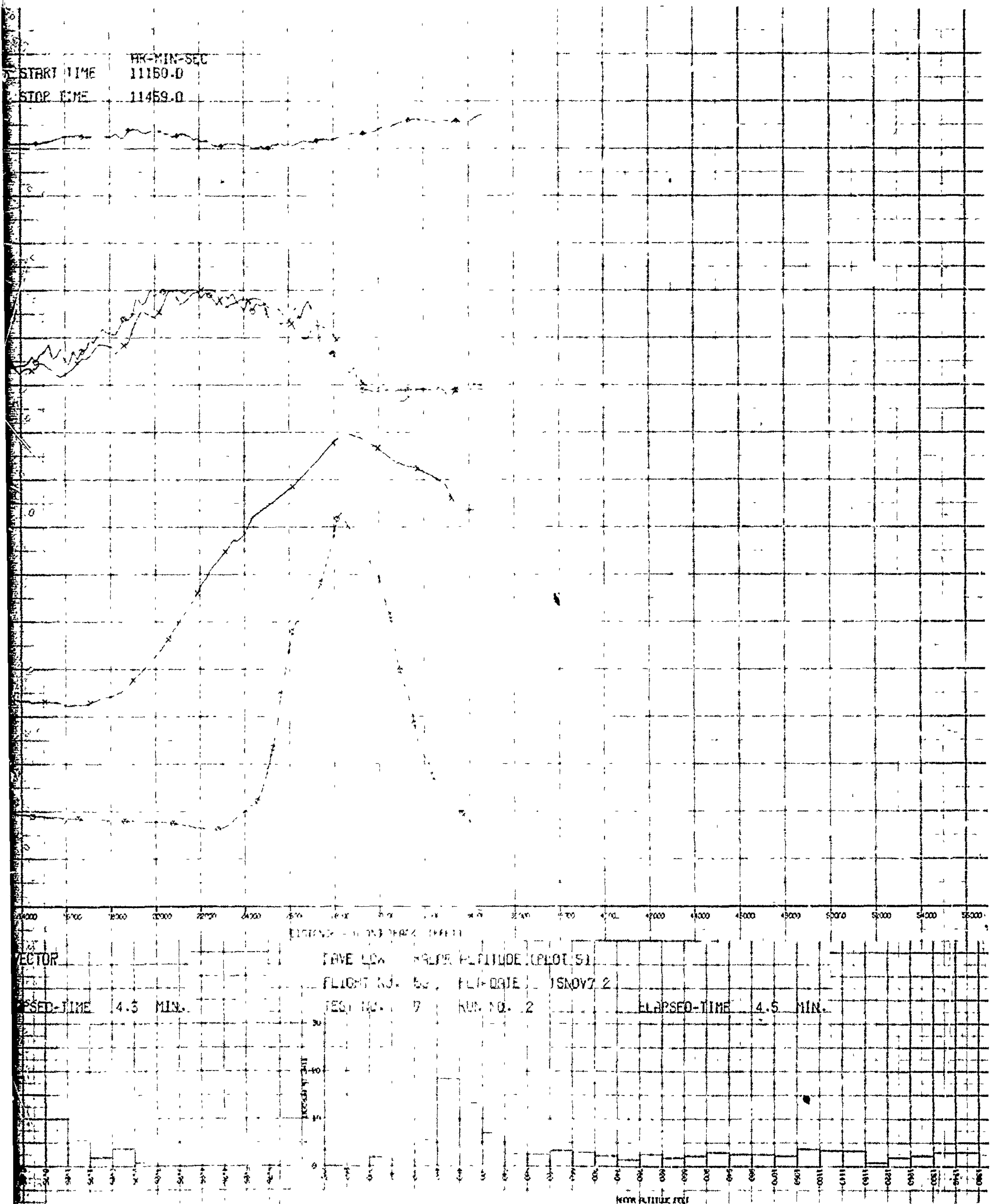
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 12



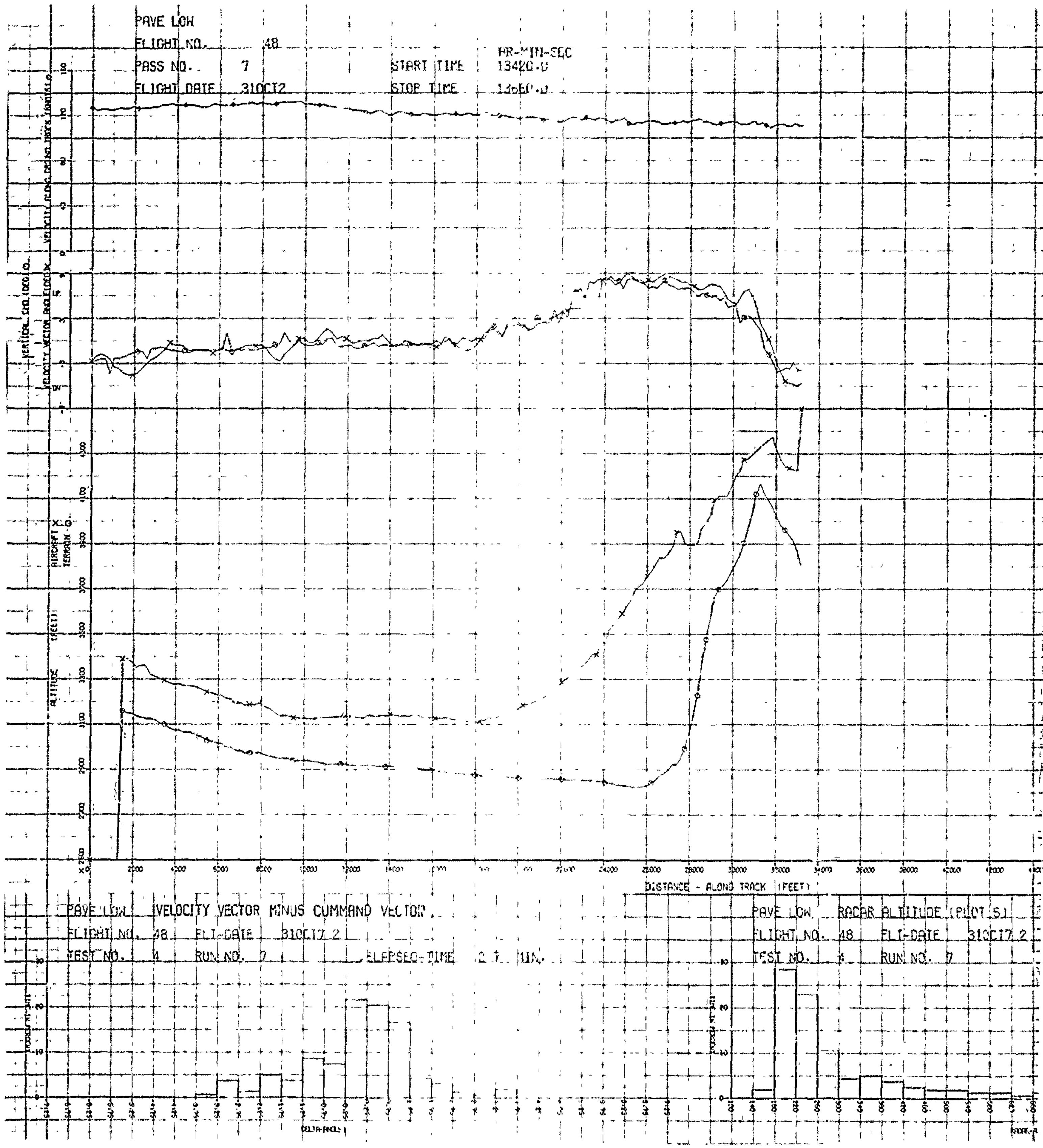
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 13



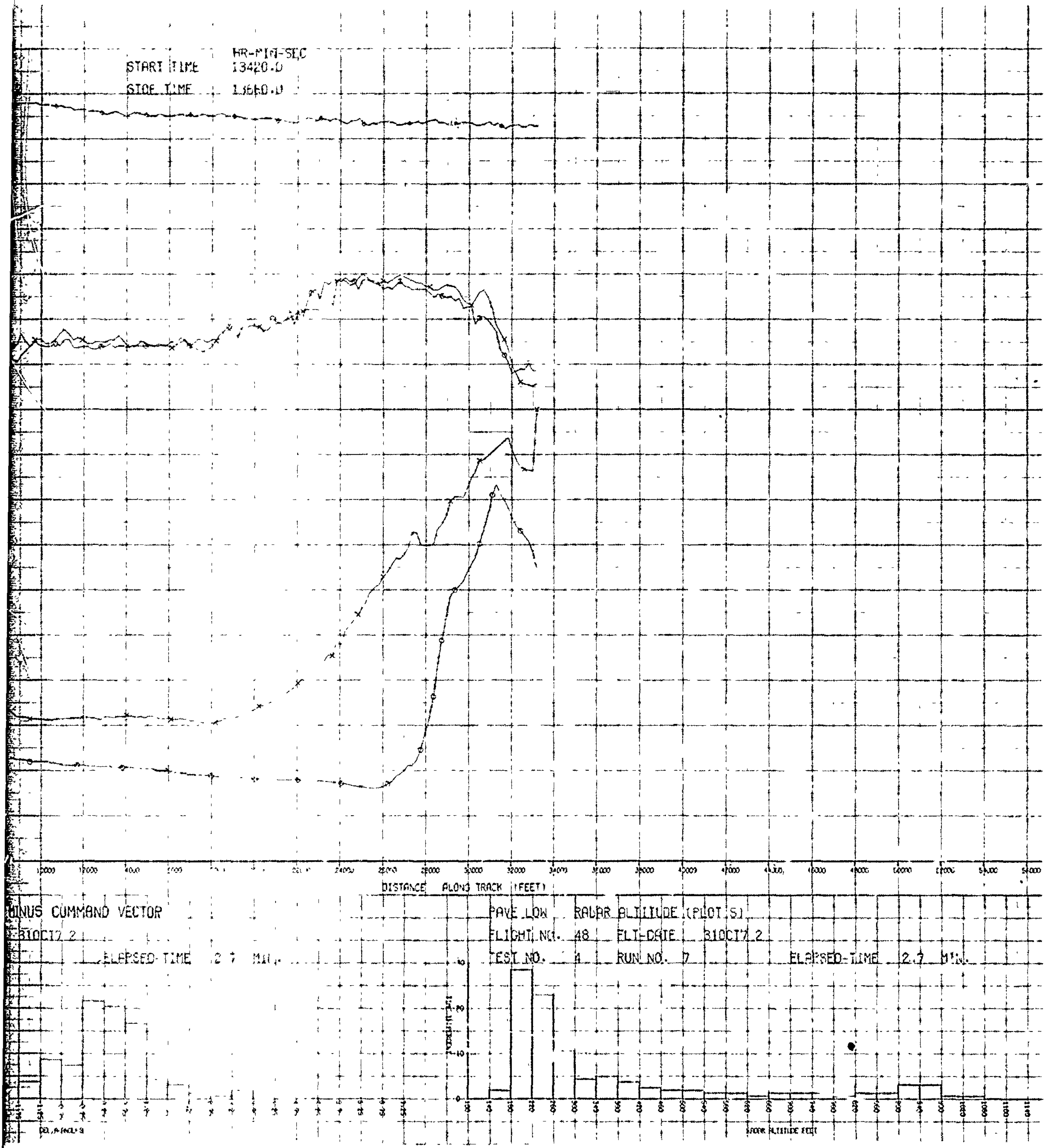
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 13



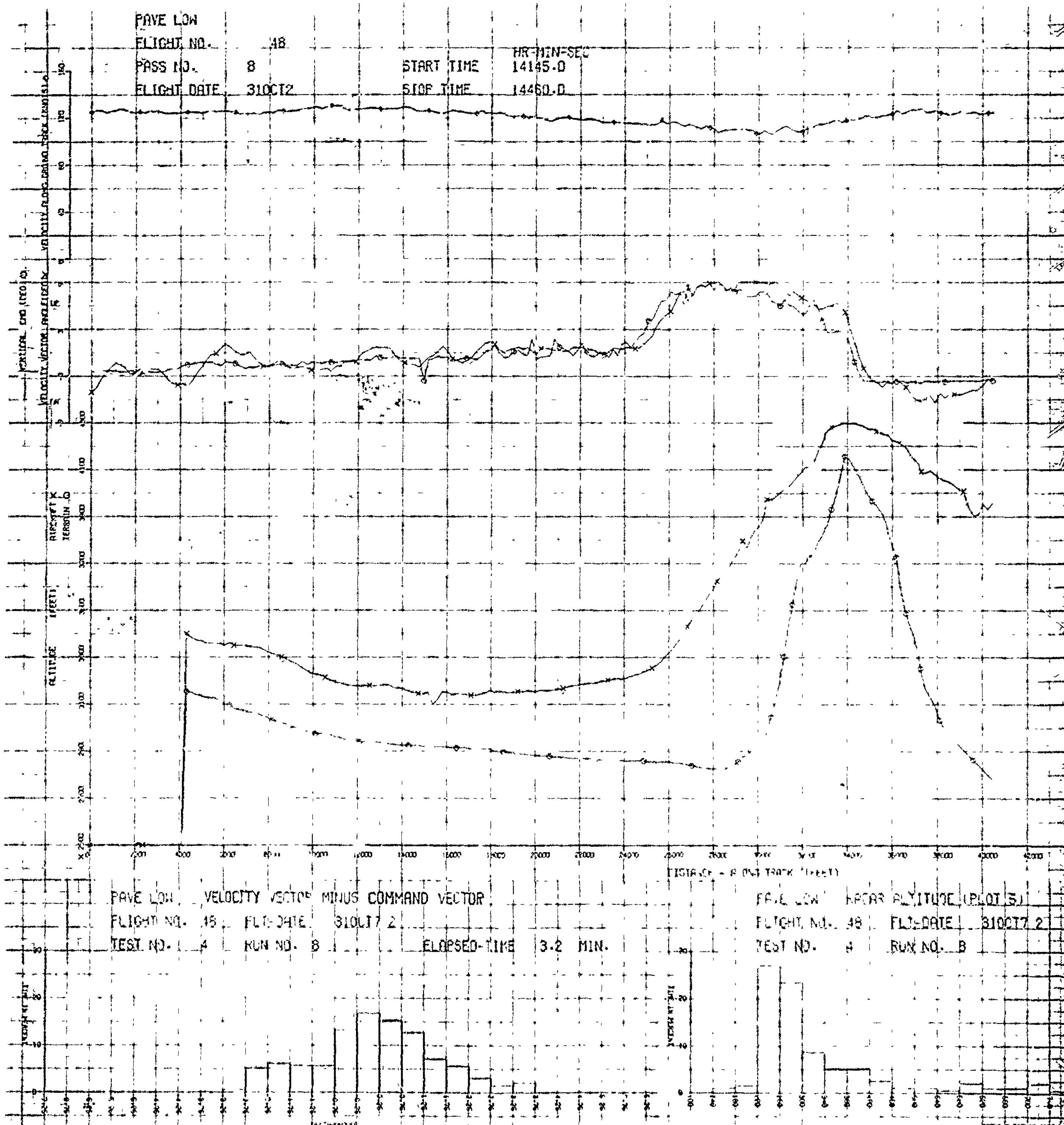
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 14



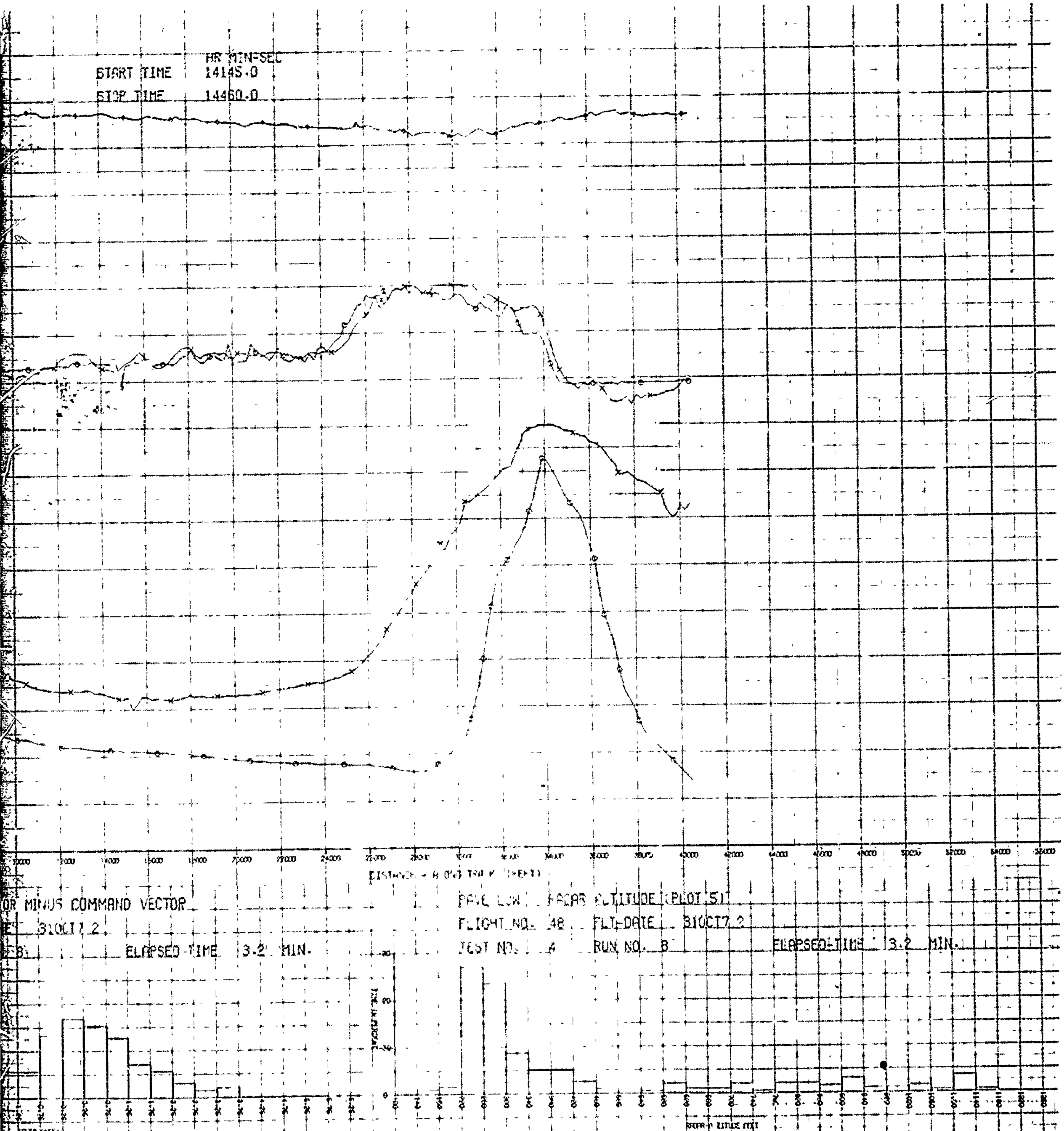
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 14



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

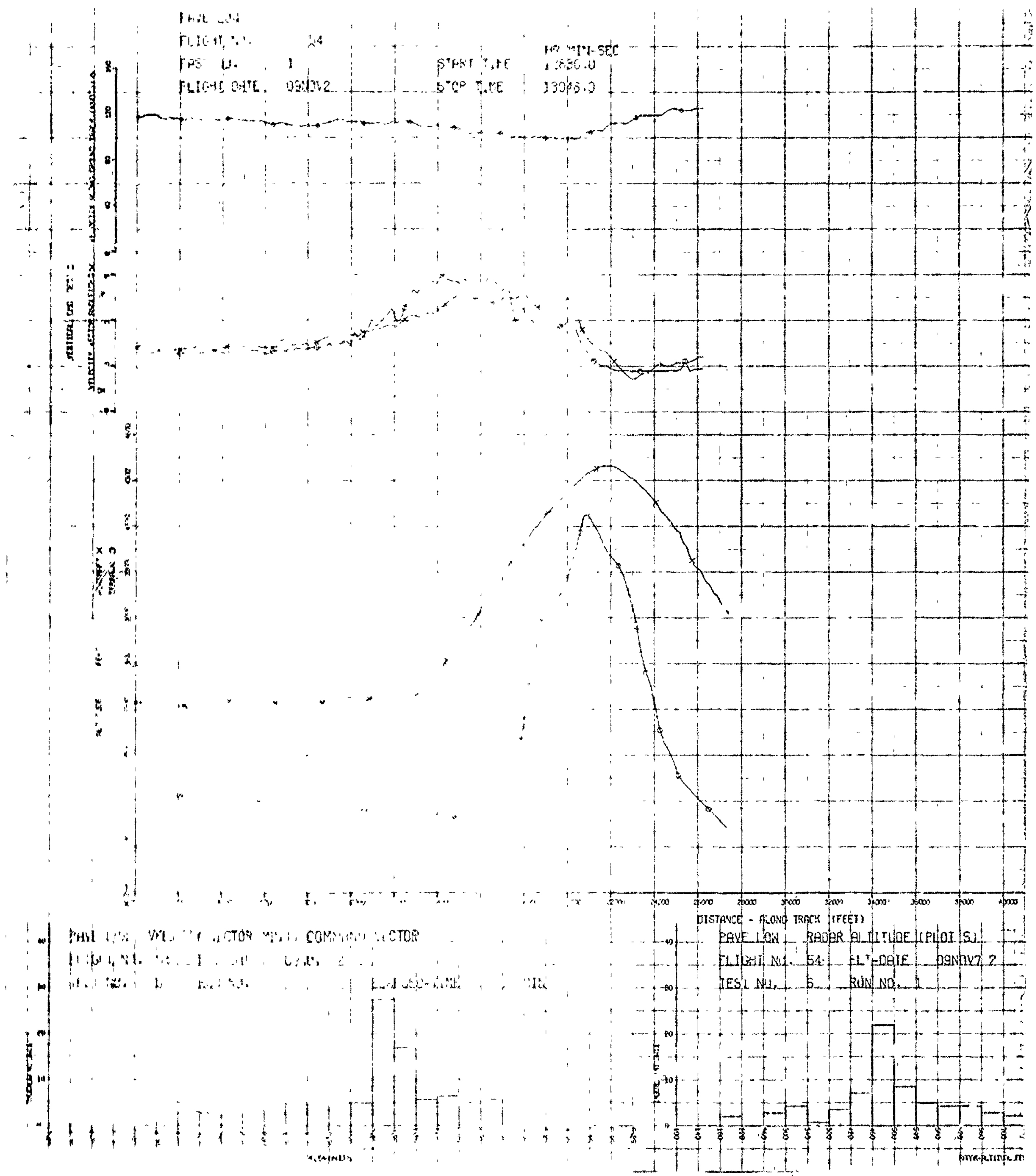
FIGURE 15



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

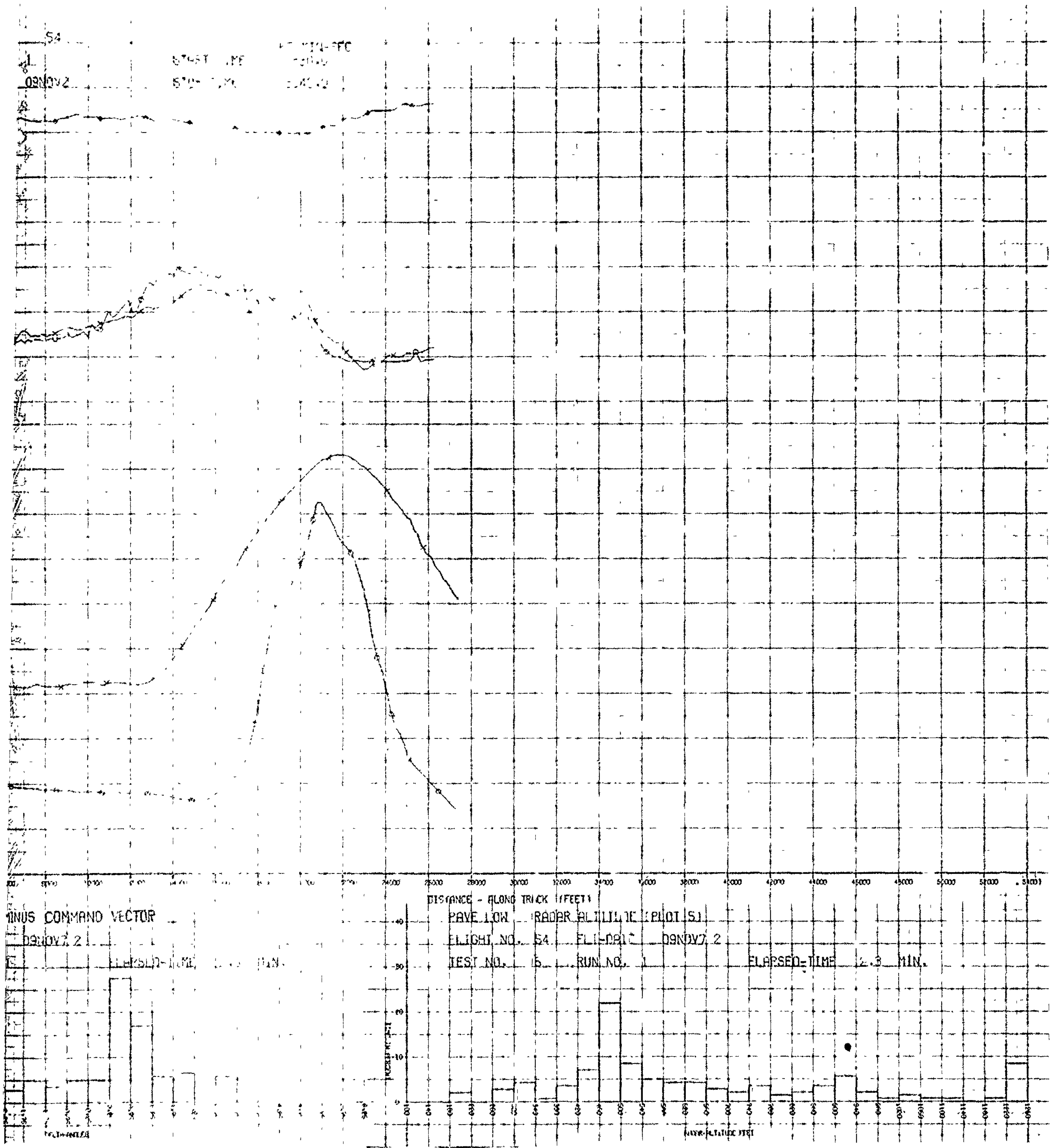
FIGURE 15

2



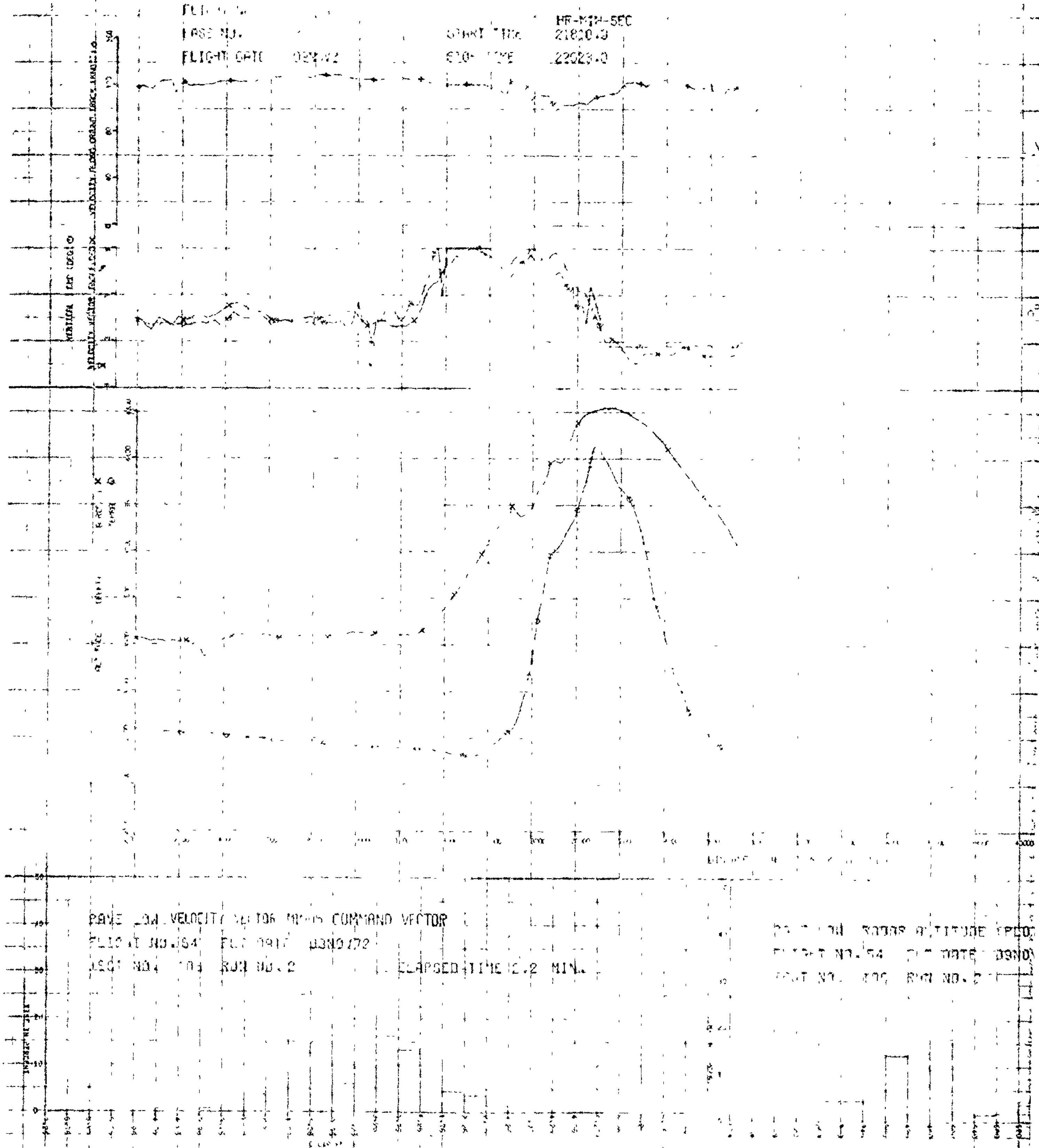
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 16



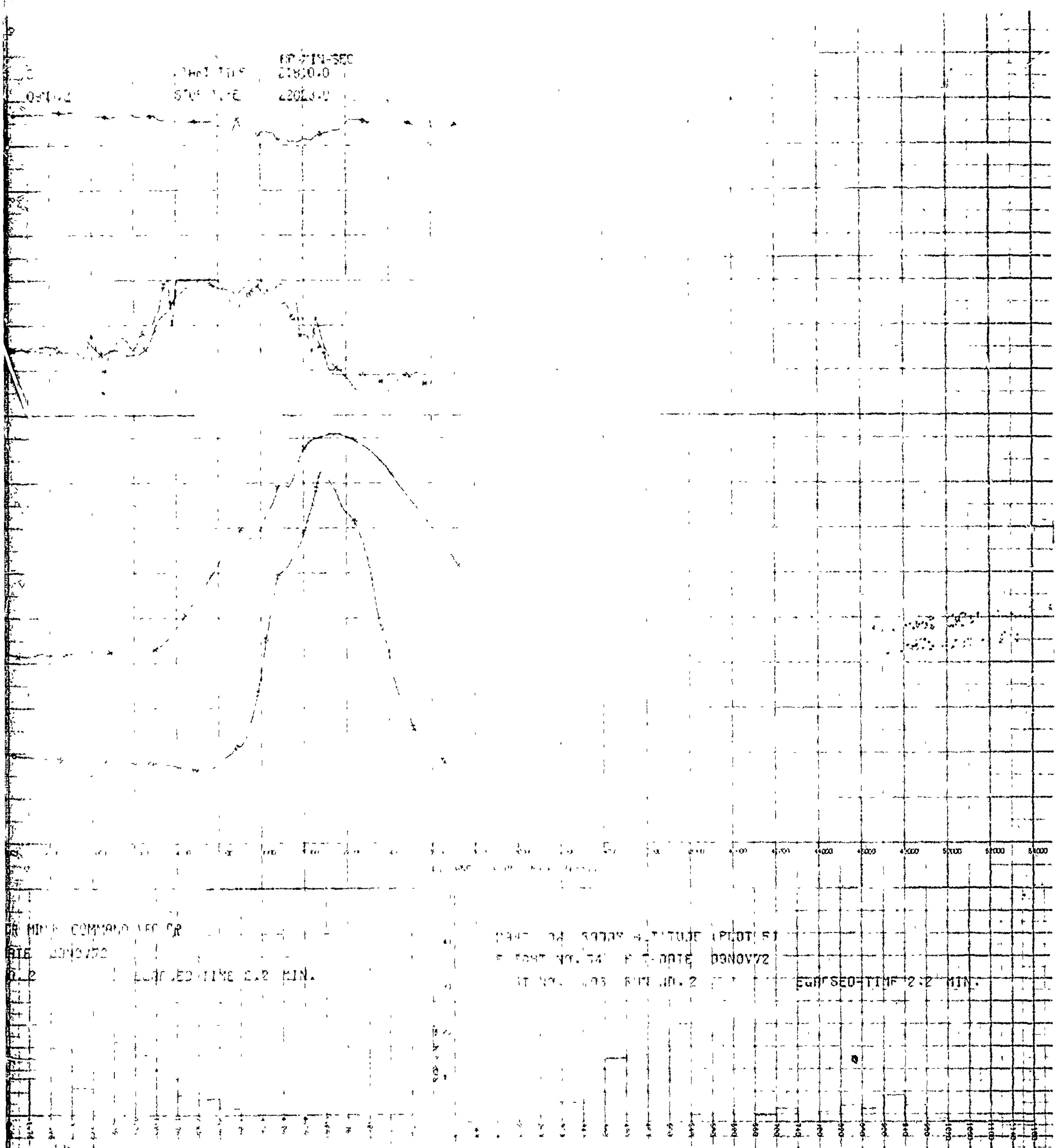
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 16



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

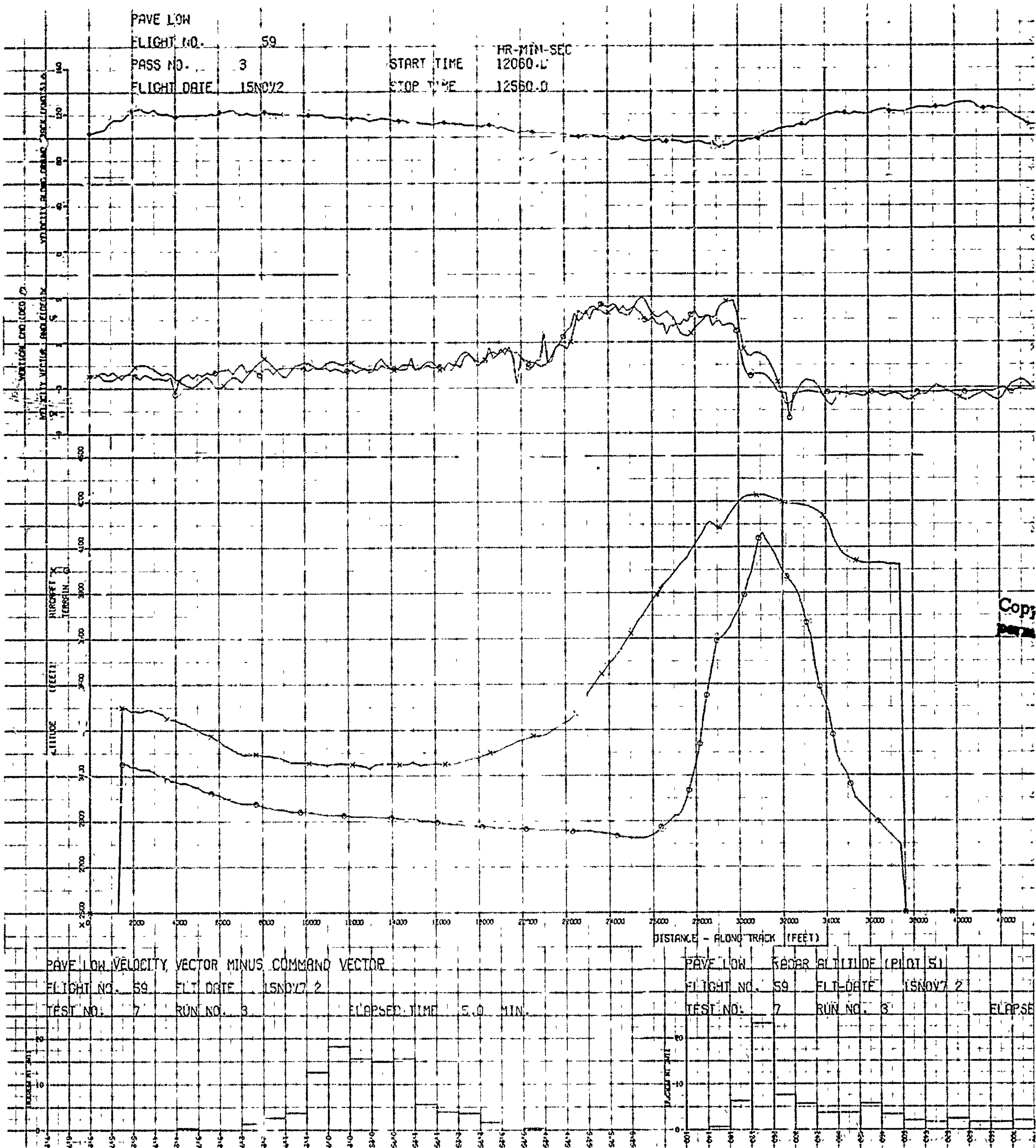
FIGURE 17



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

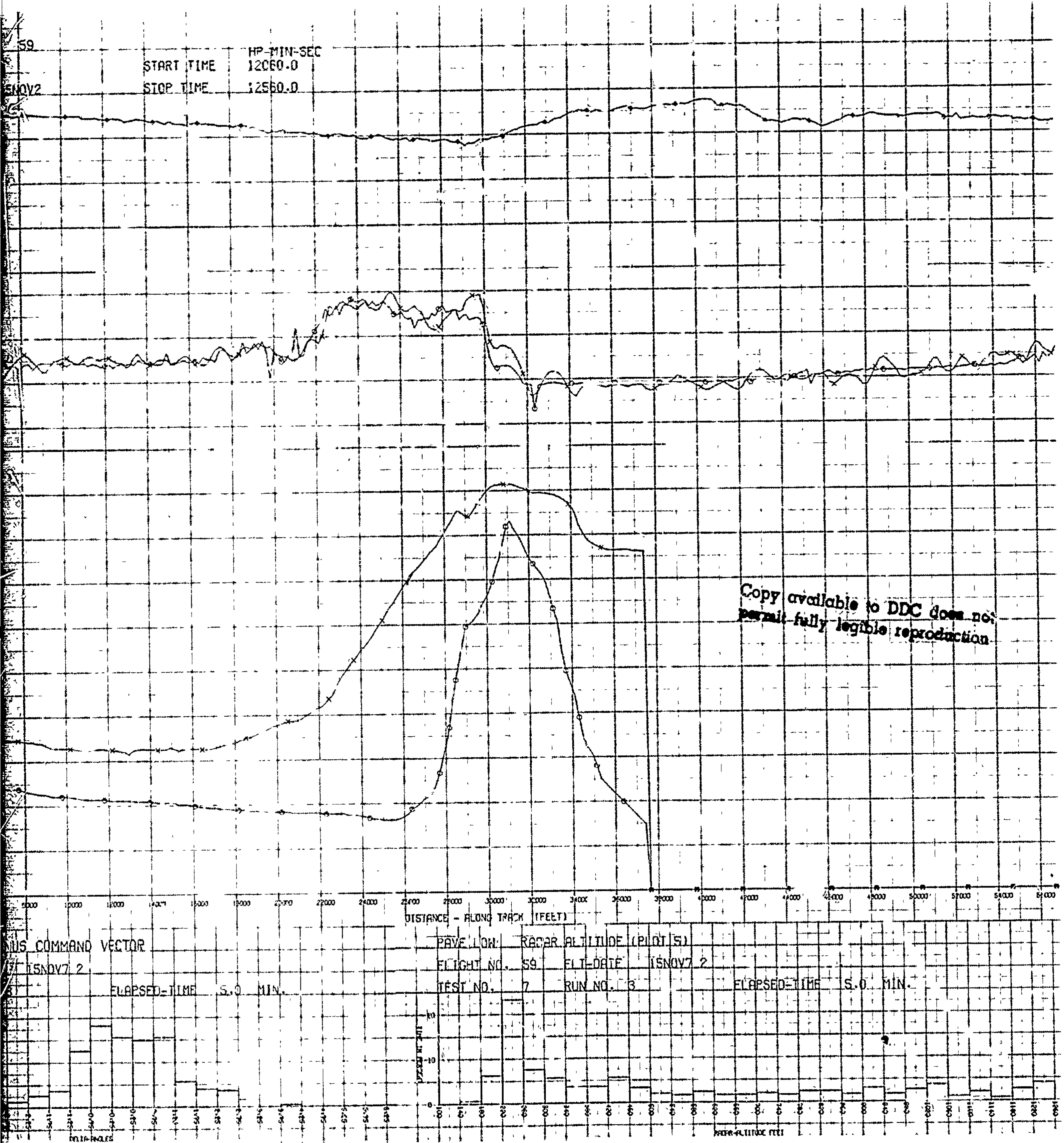
FIGURE 17

2



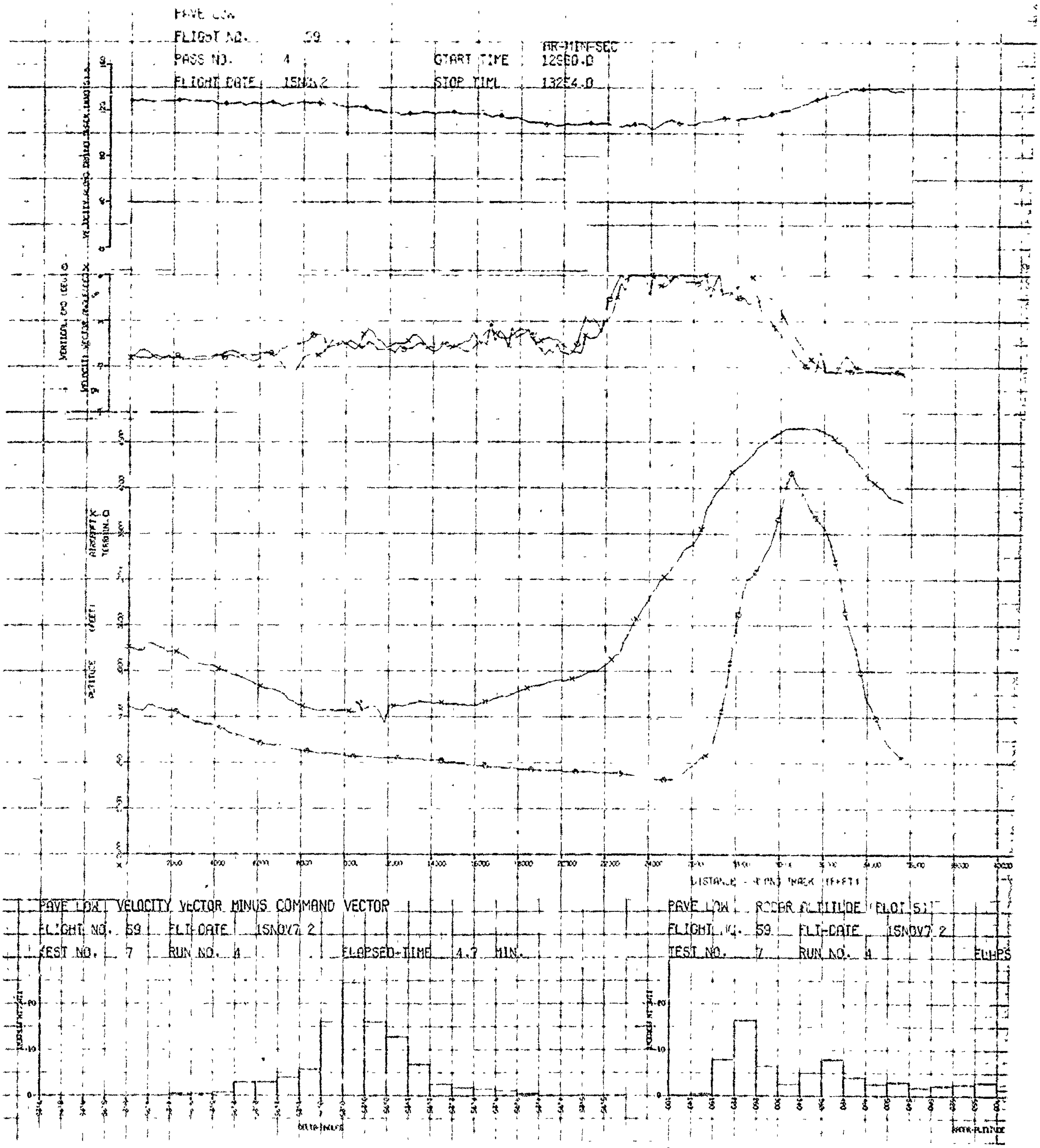
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 18



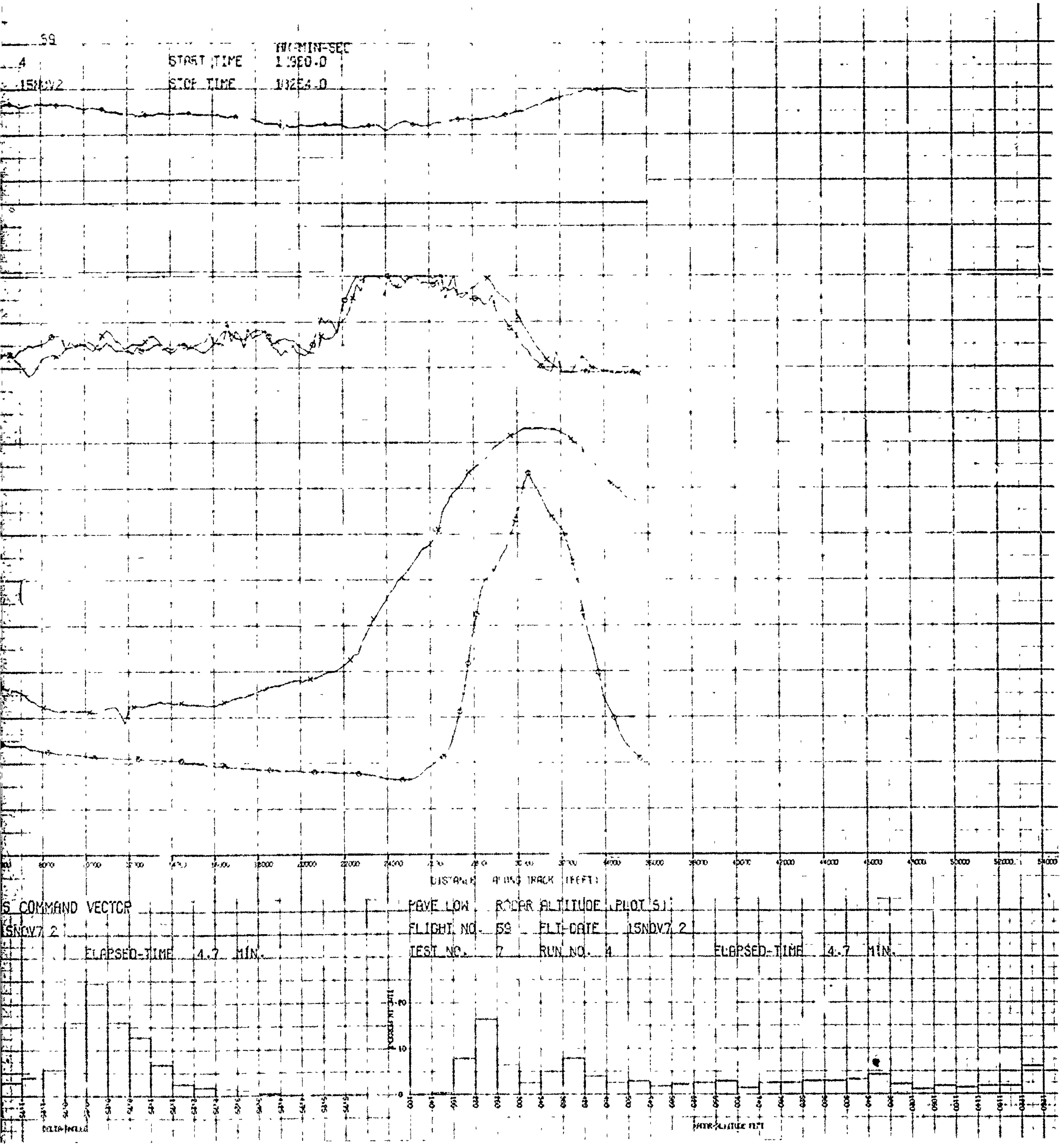
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 18



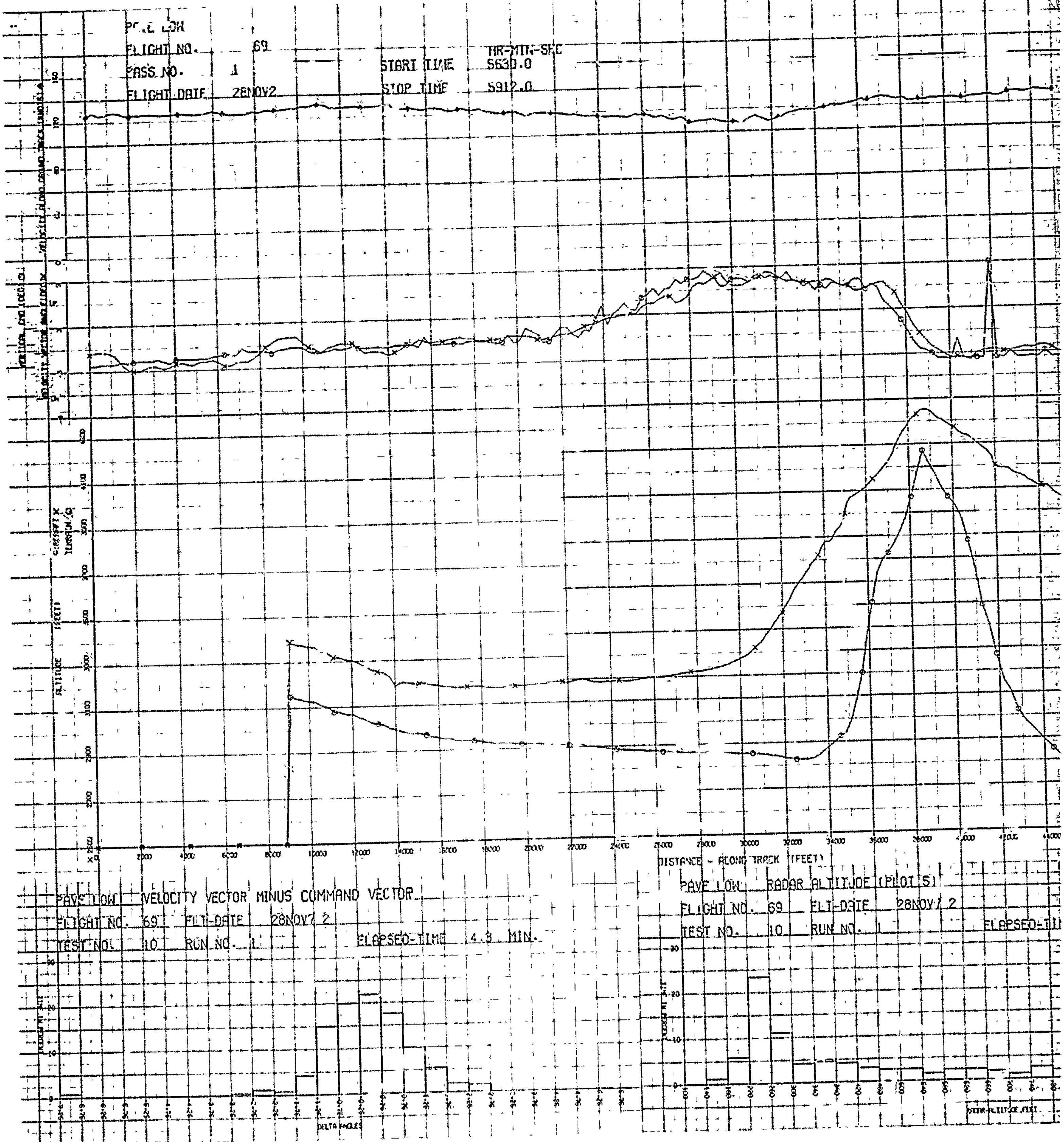
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 19



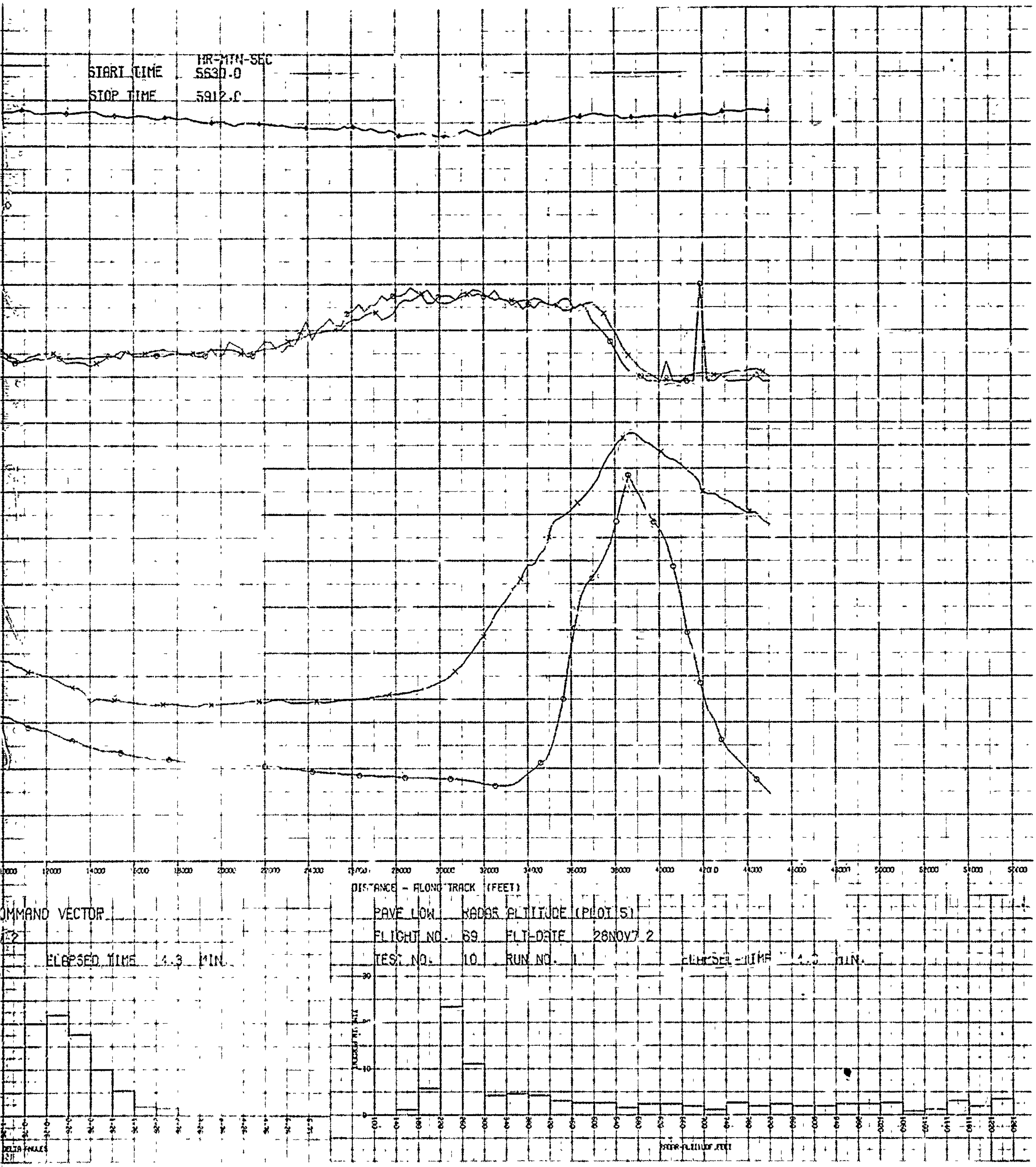
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 19



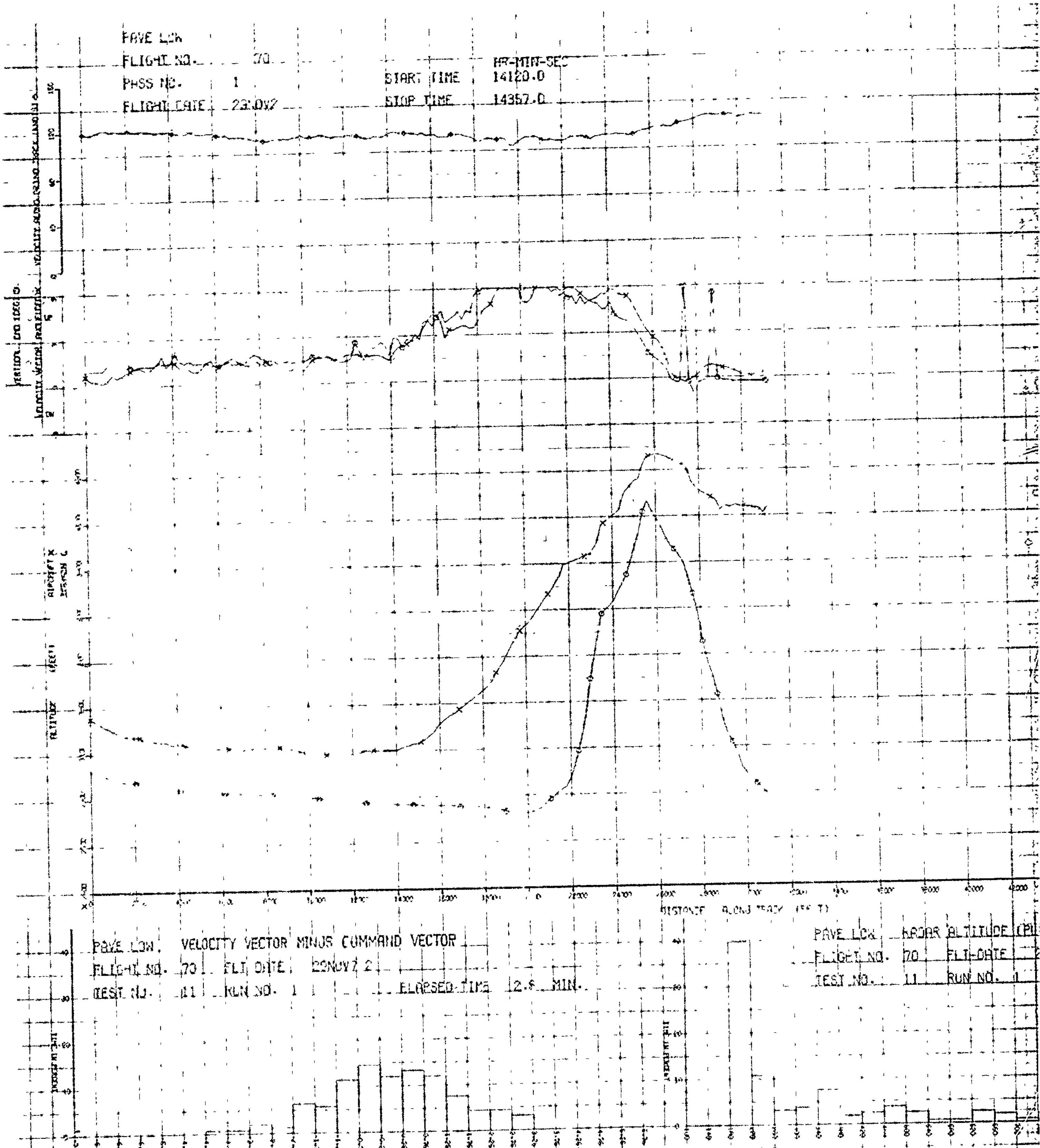
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 20



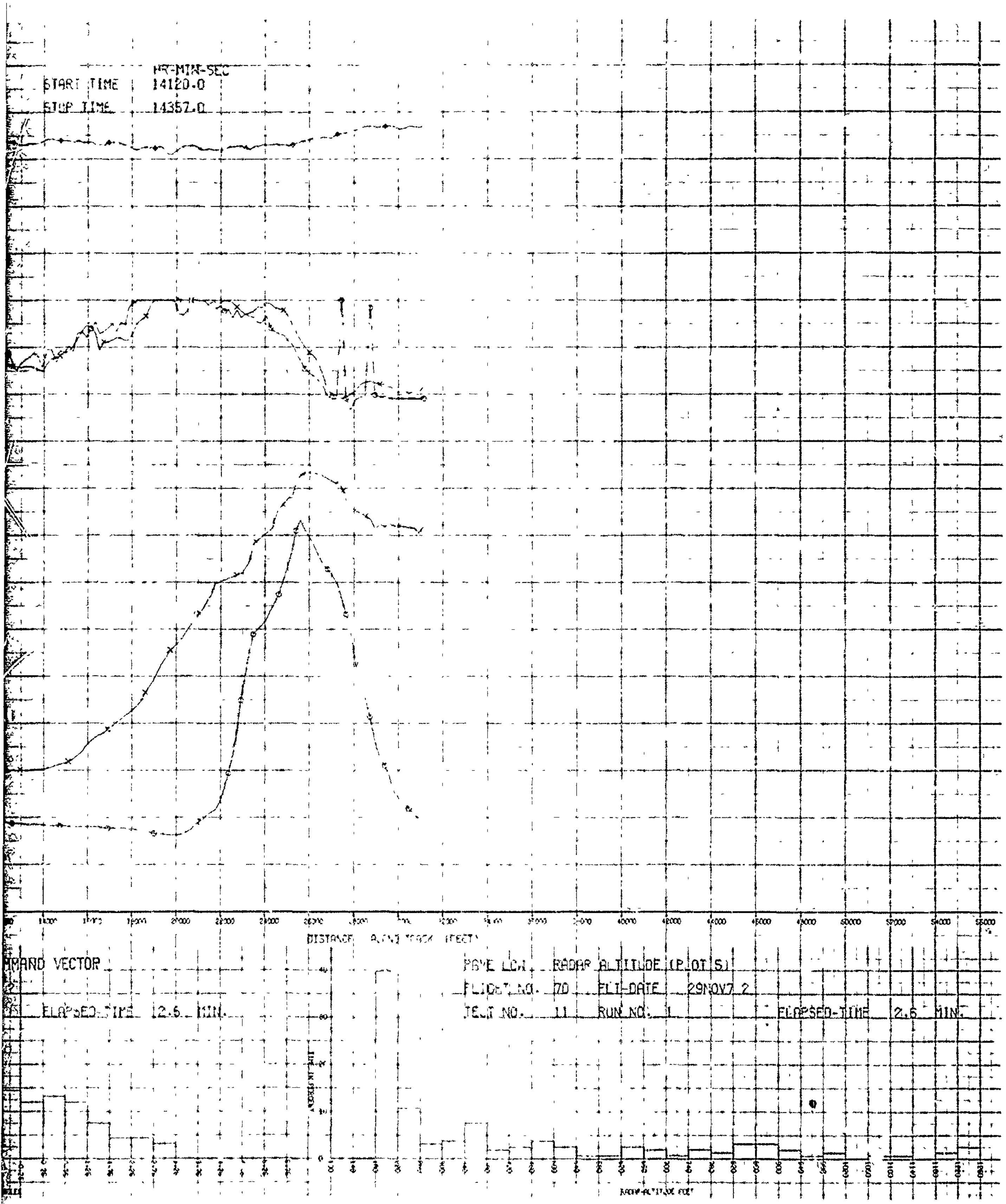
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 20



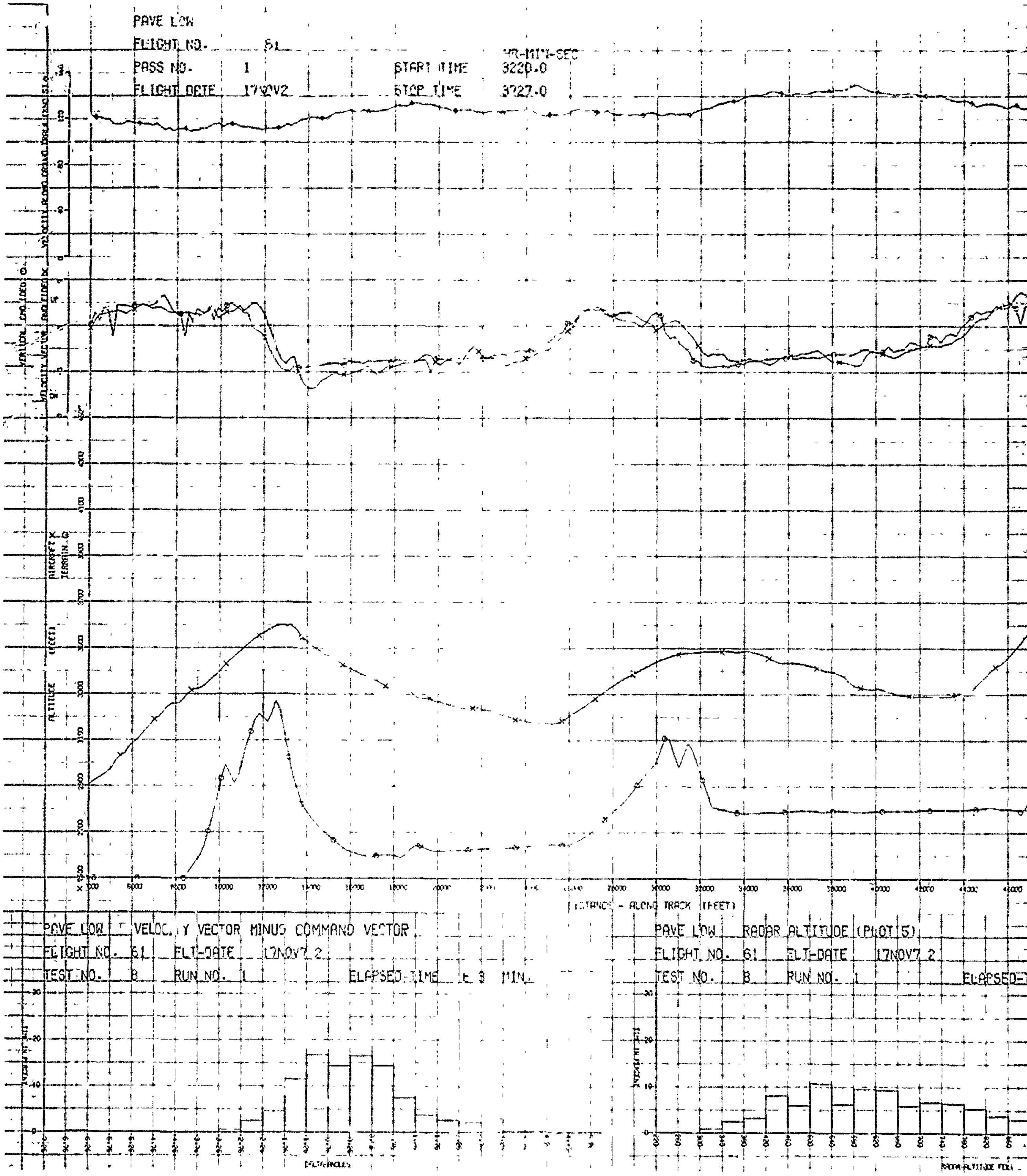
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 21



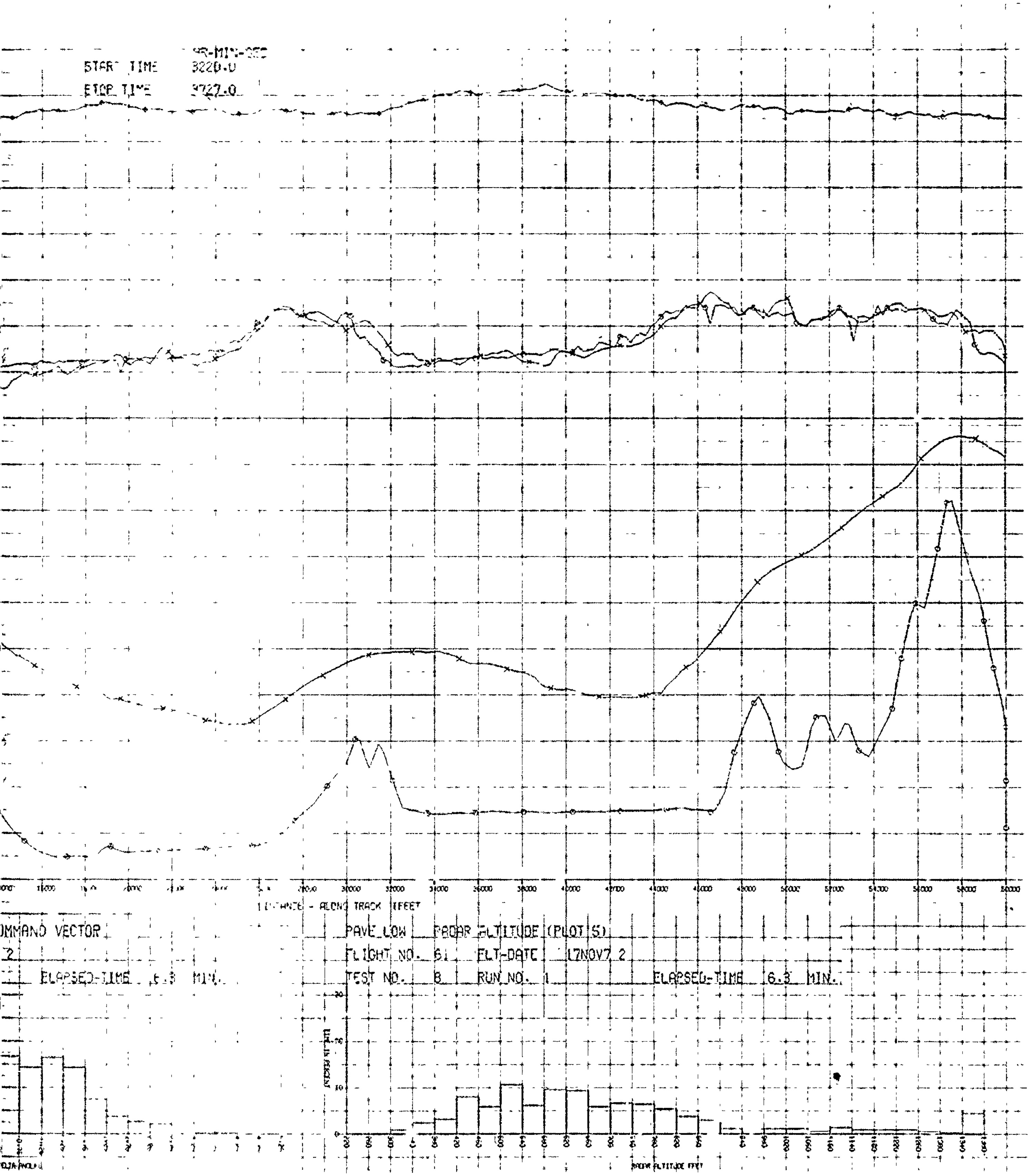
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 21



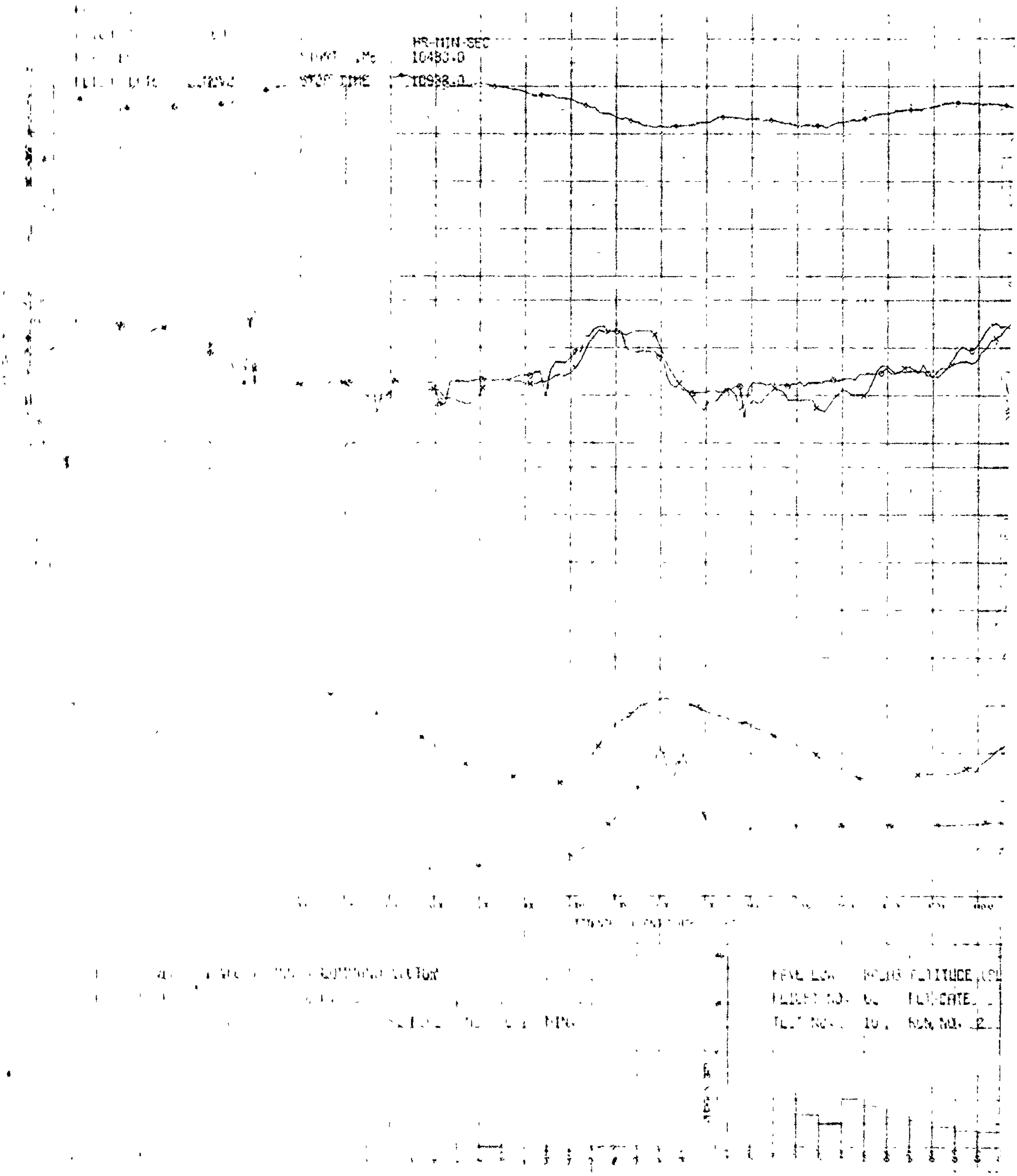
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 22



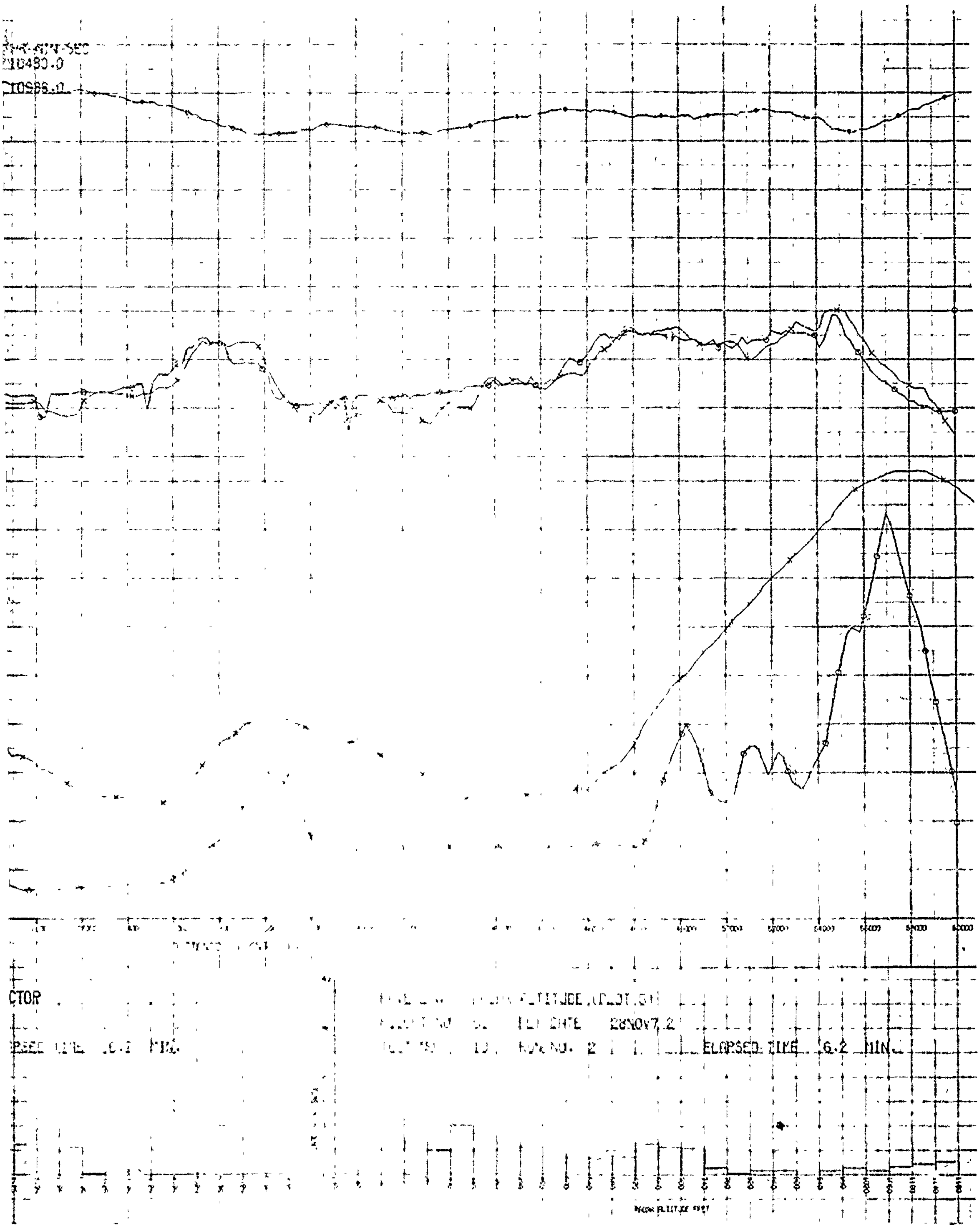
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 400FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 22



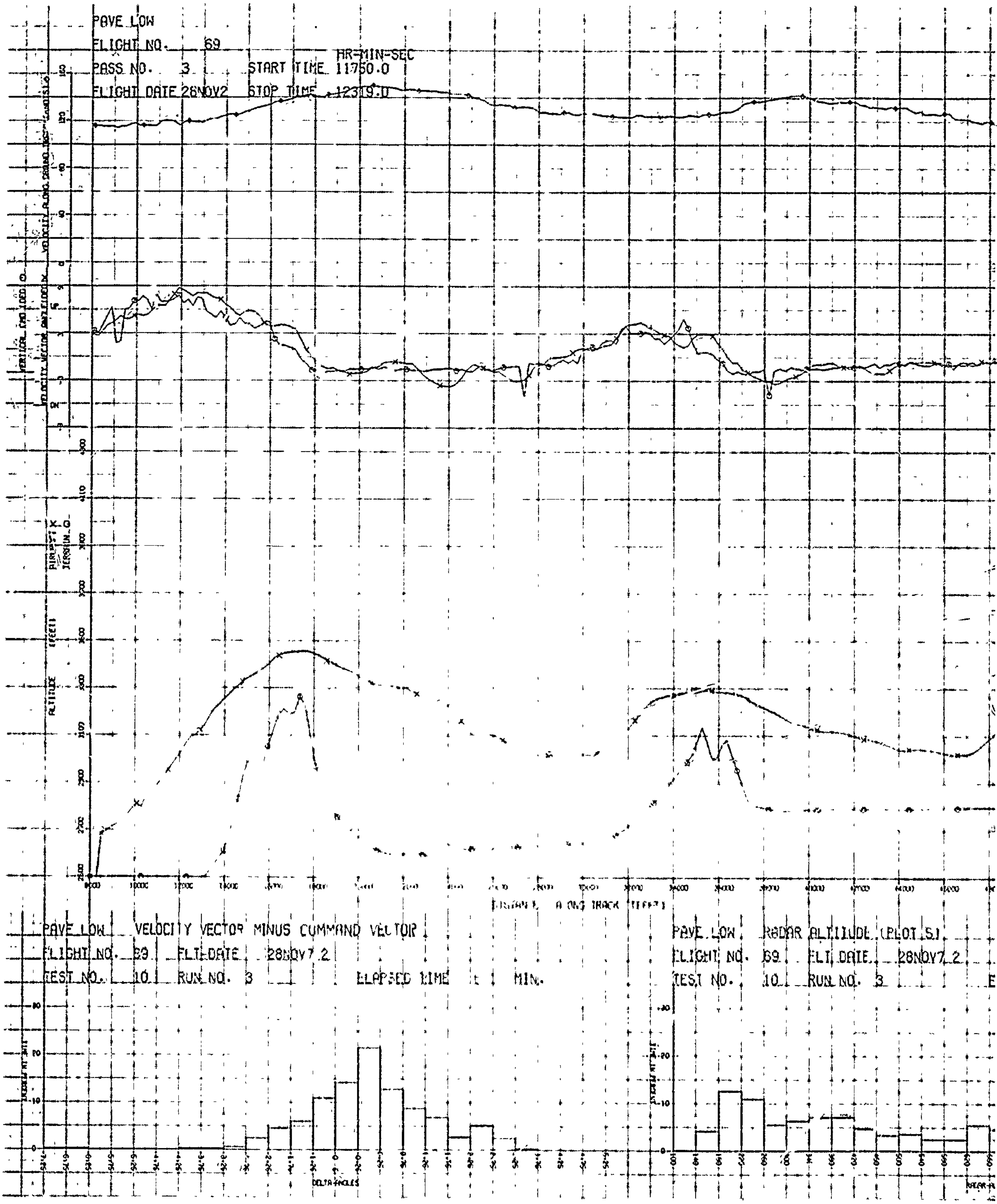
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 23



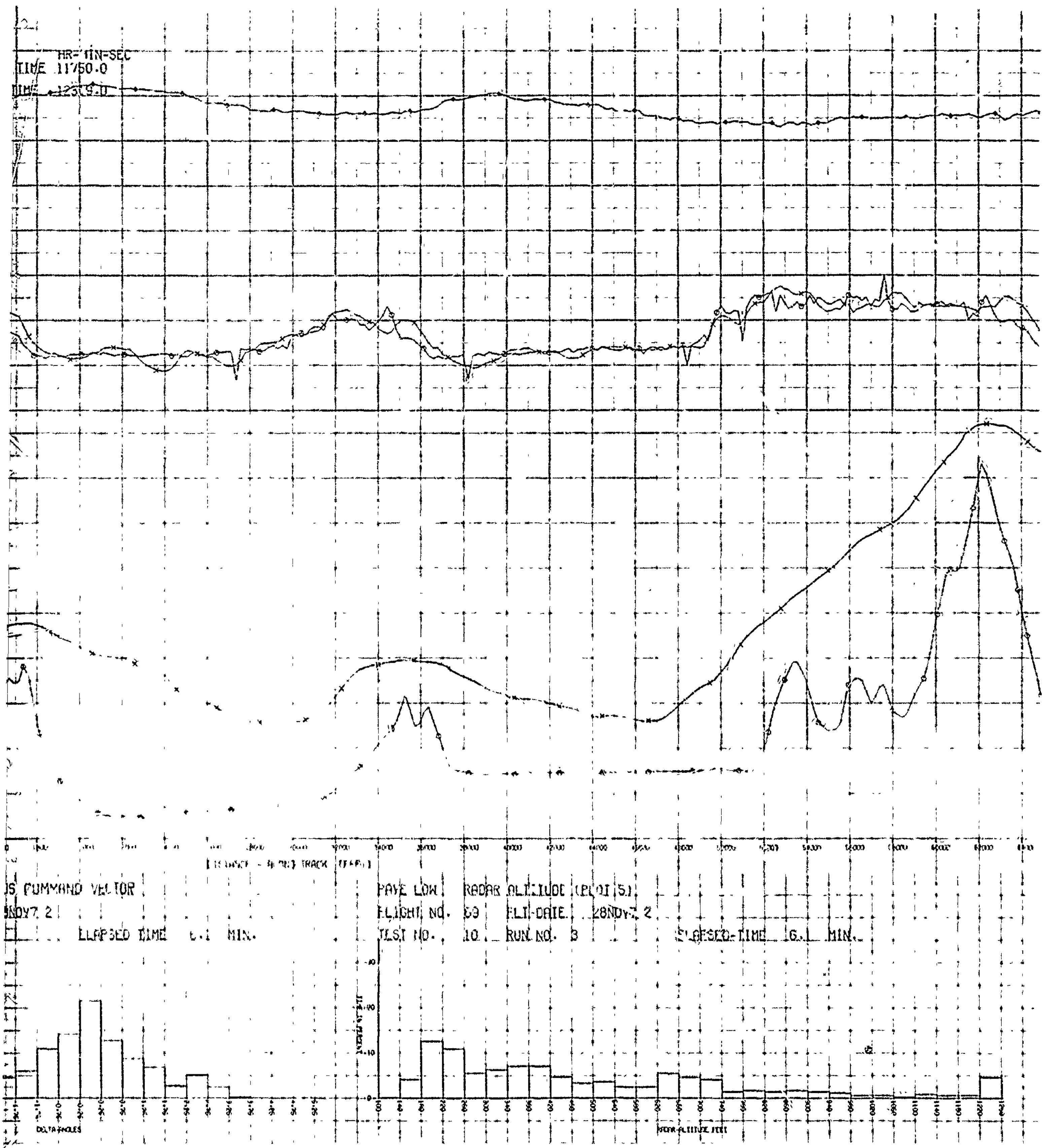
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 23



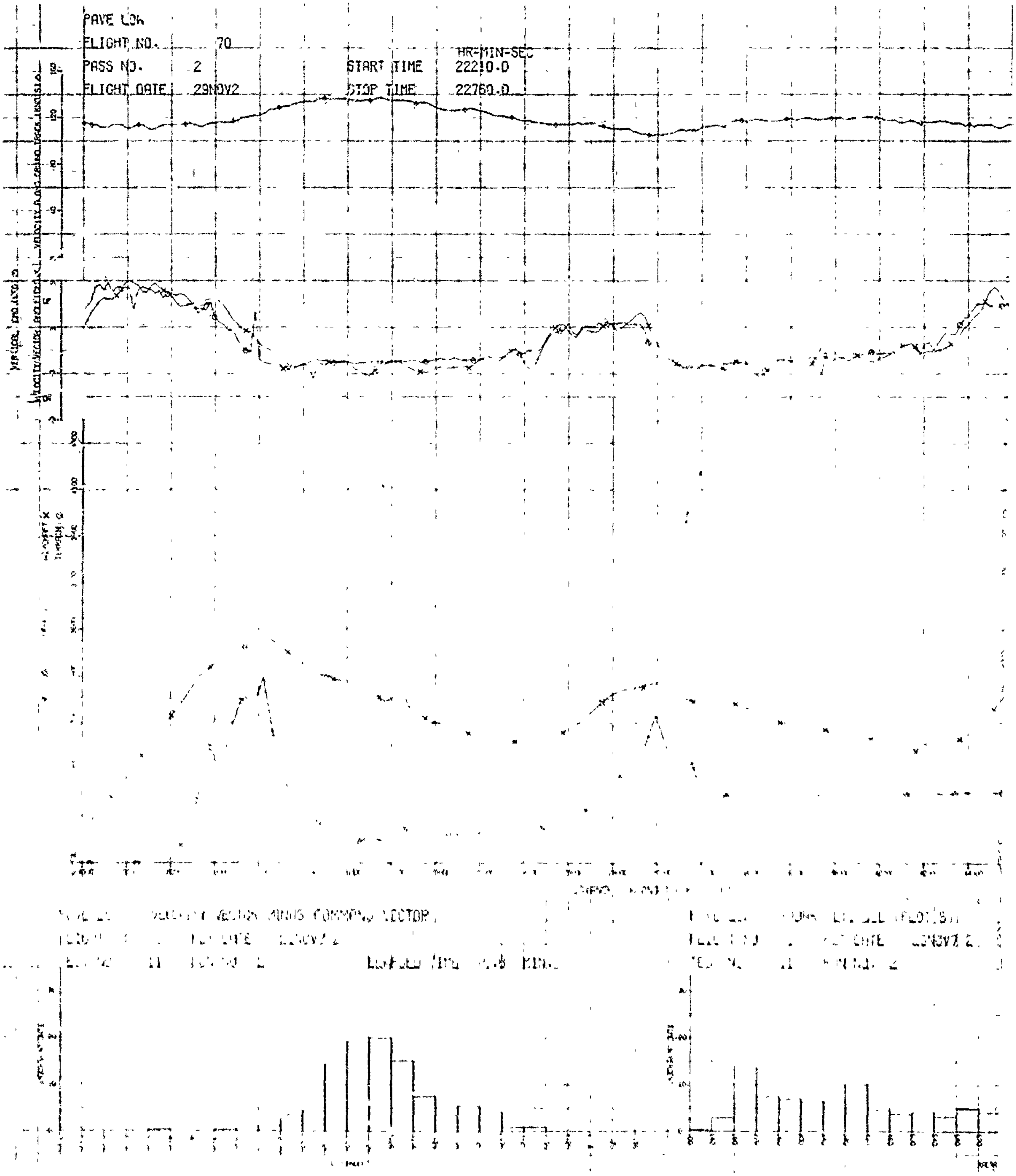
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 24



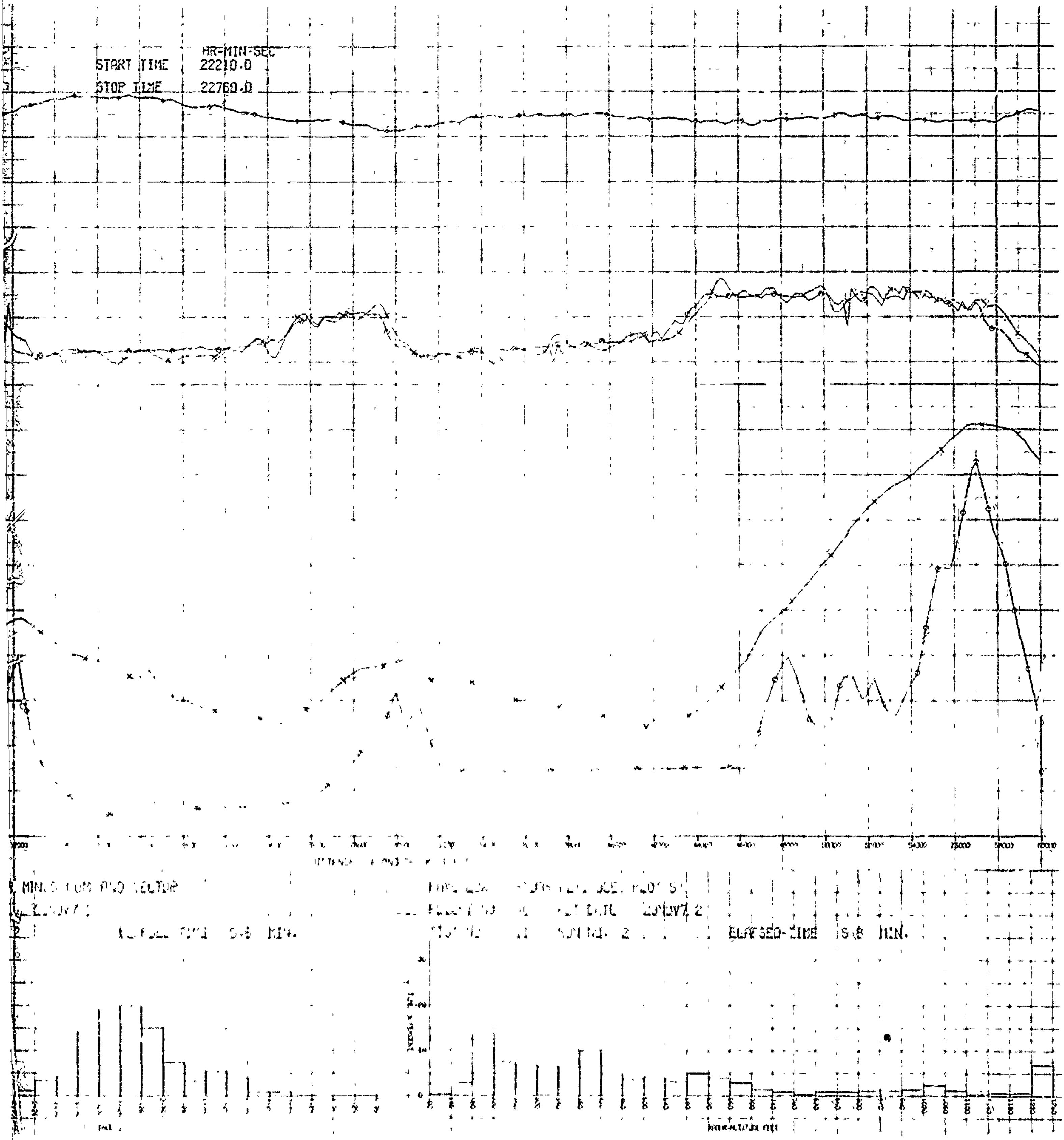
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 24



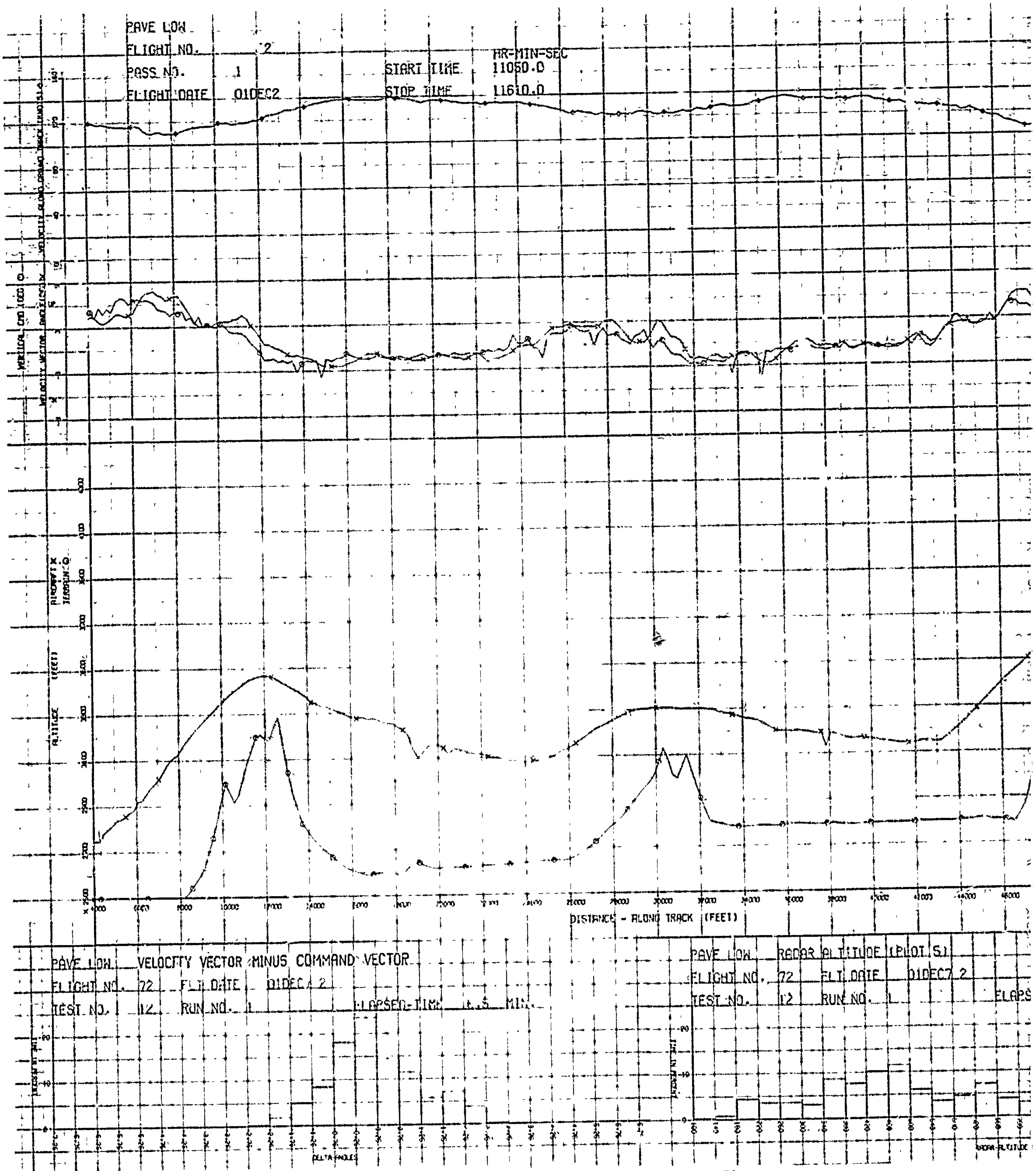
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN-FOLLOWING COMMAND ON

FIGURE 25



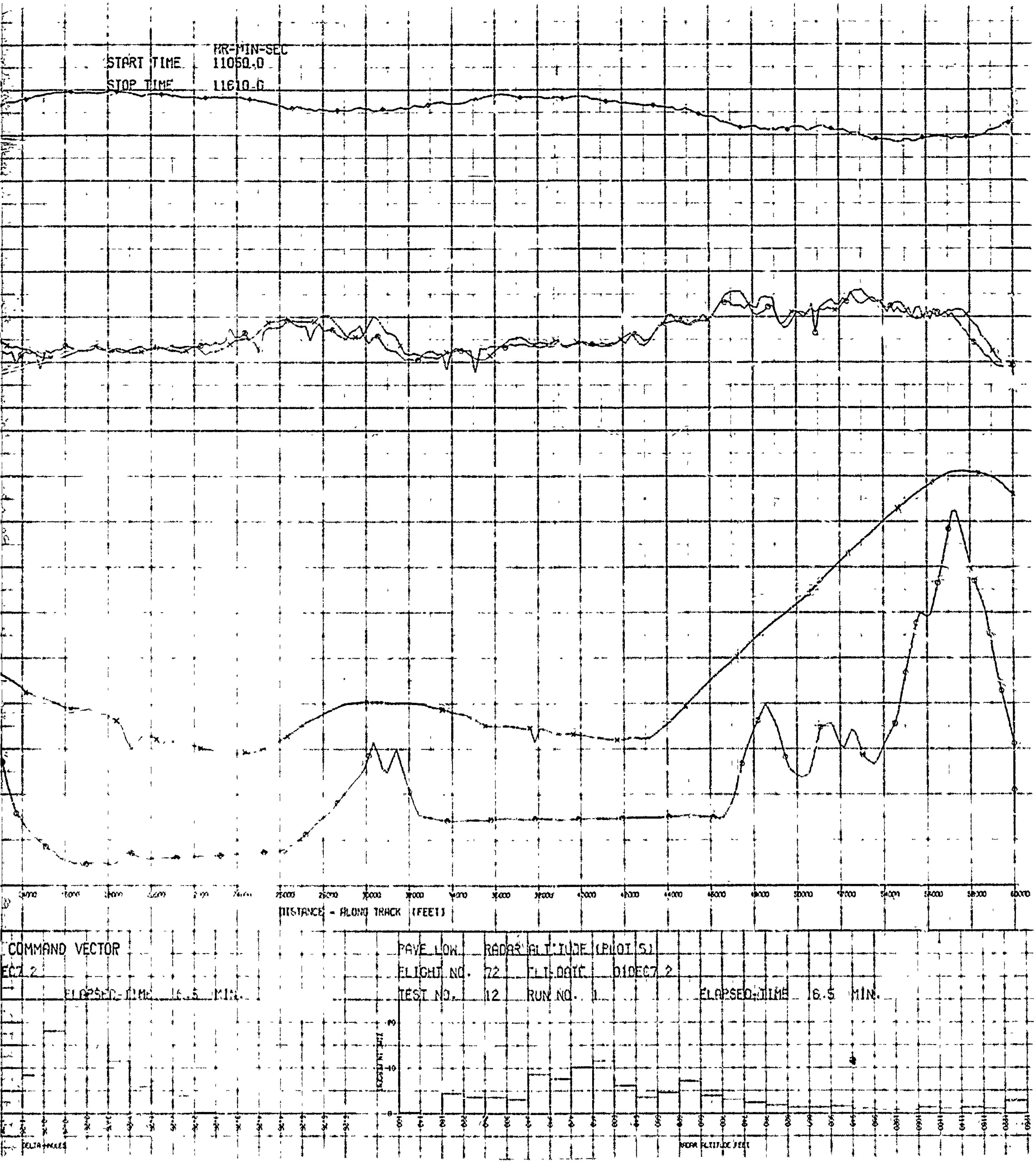
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 25



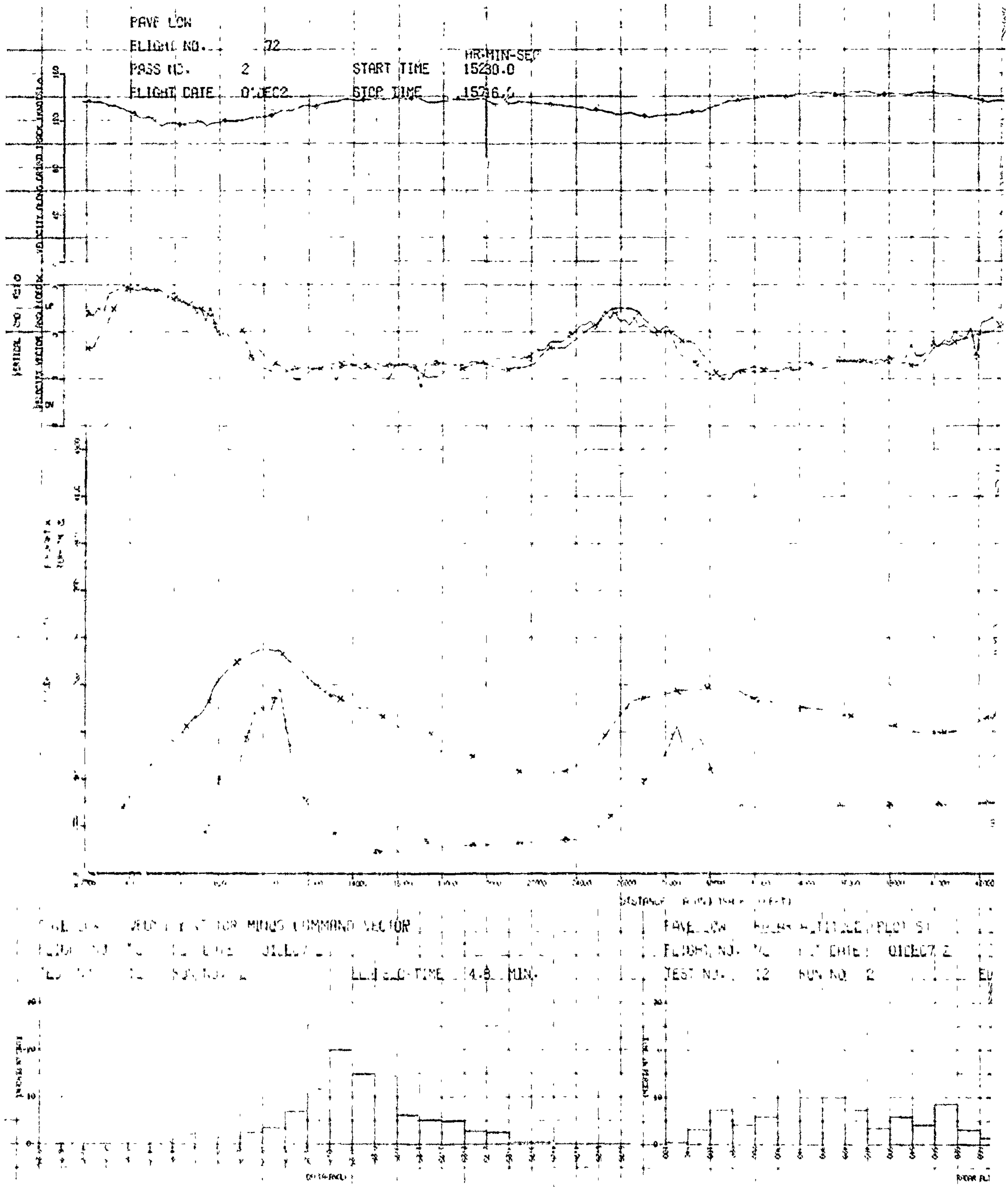
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 26



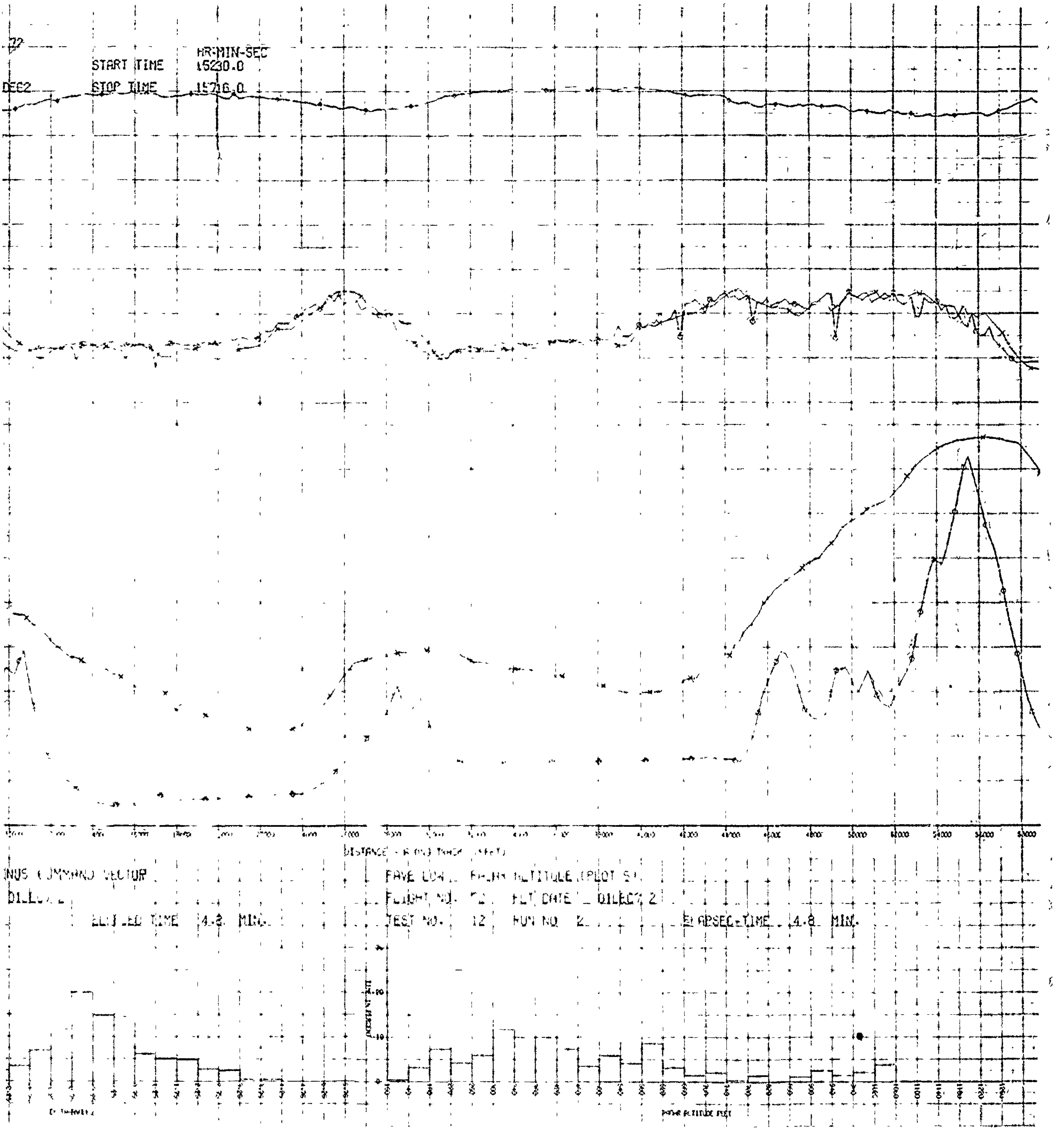
NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 26



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 27



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 27

2

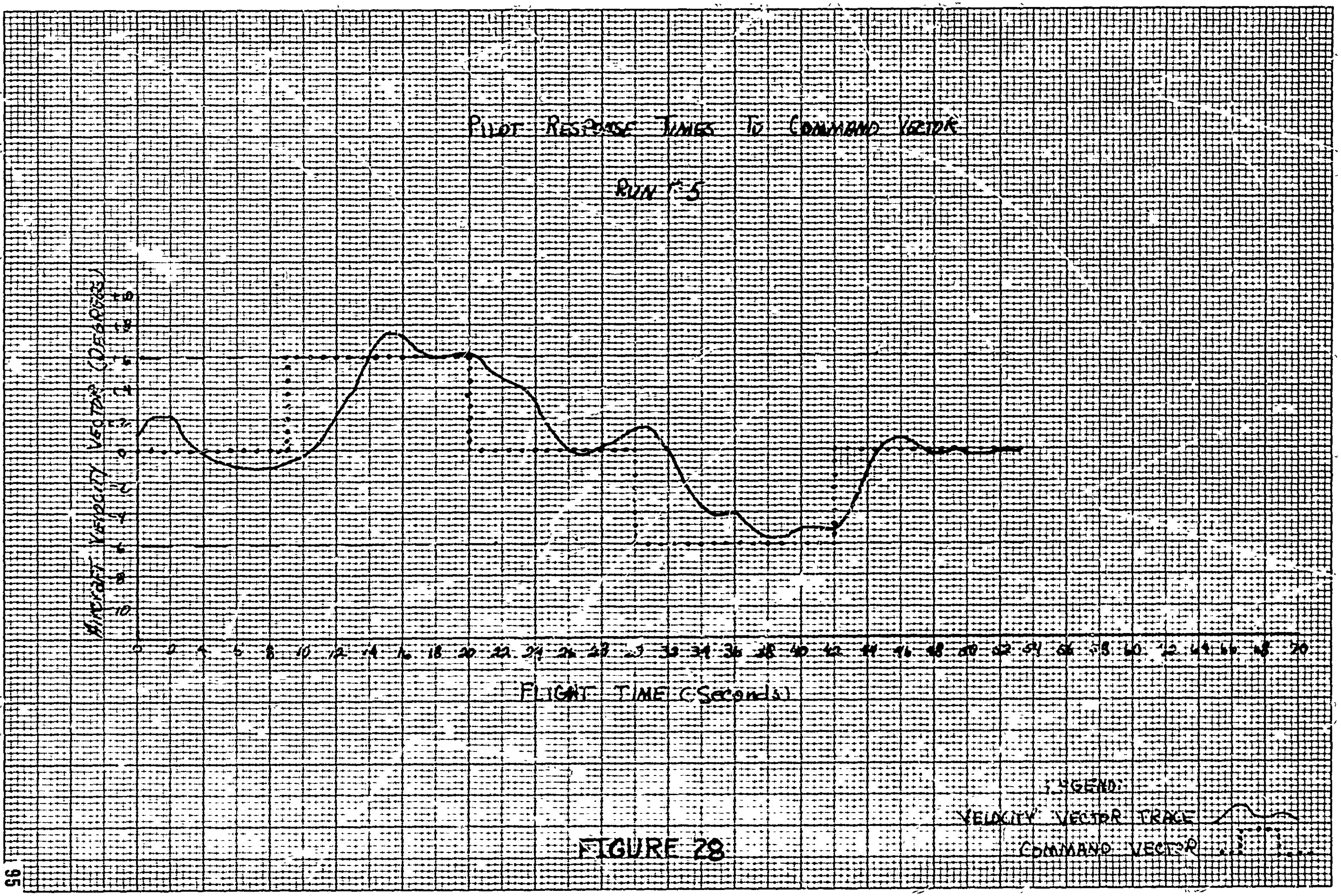

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN 5
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (Seconds)
LEGEND:
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 28

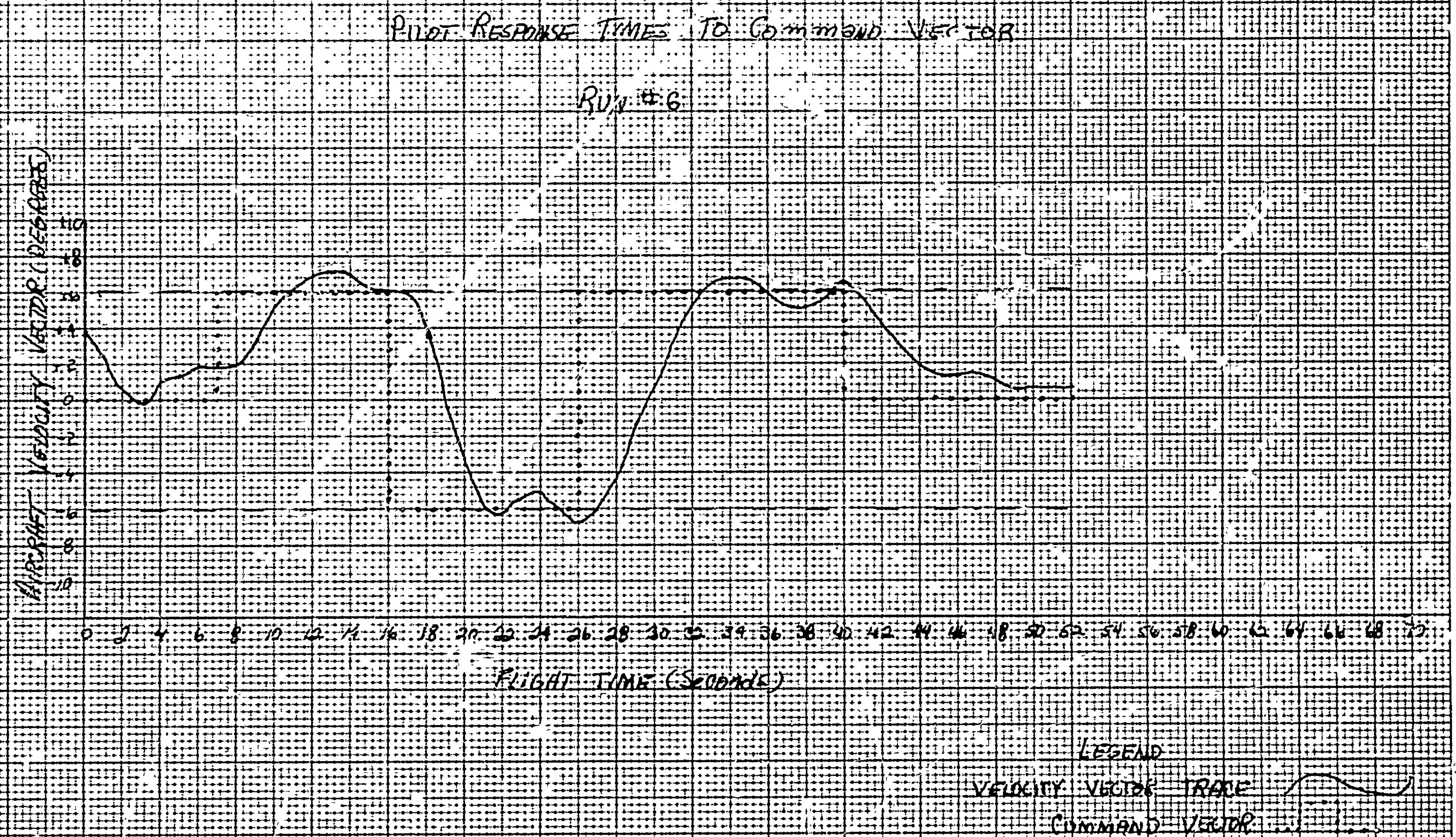

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN #6
AIRCRAFT VELOCITY VECTOR (DEGREES)
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70
FLIGHT TIME (SECONDS)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 29

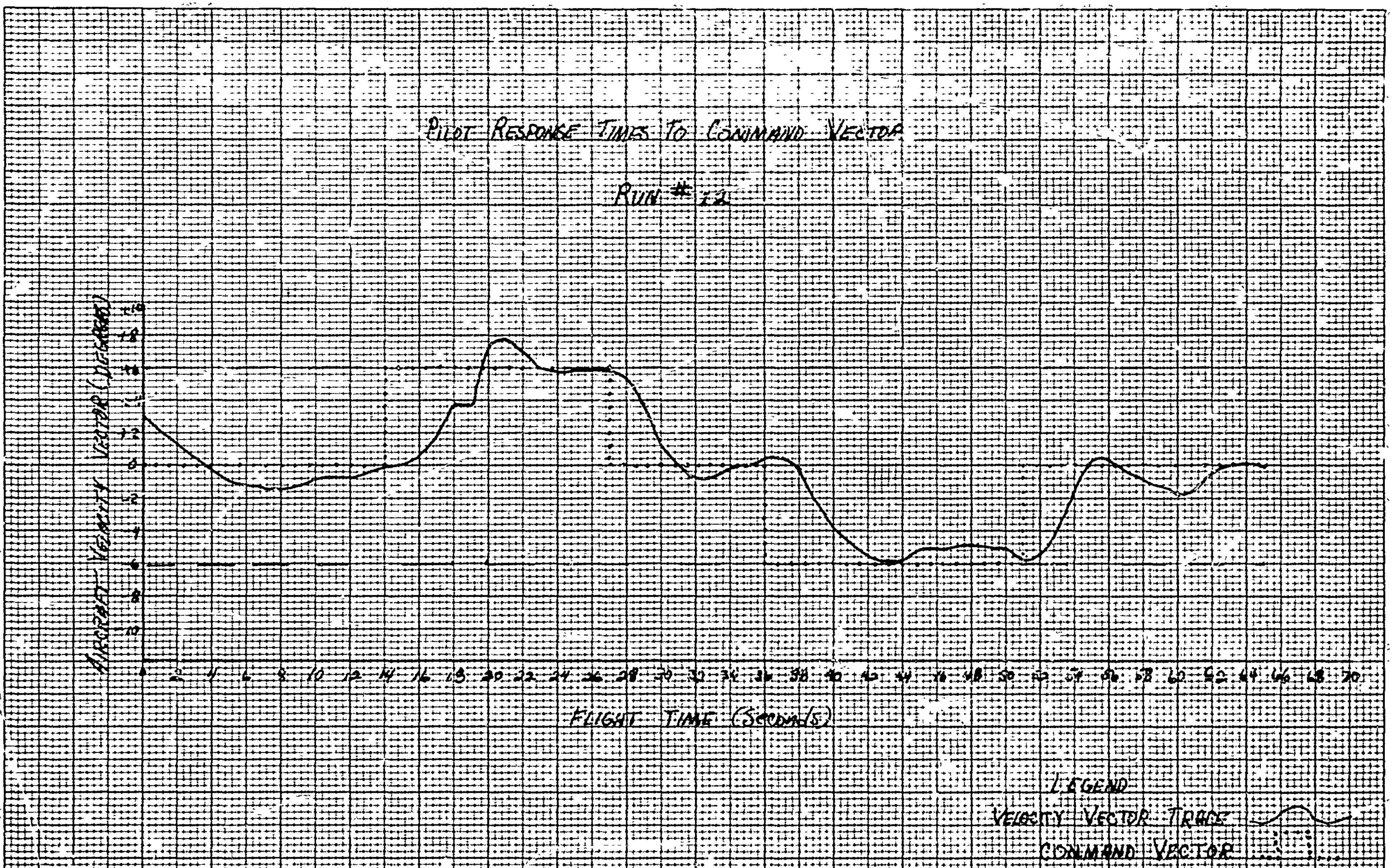

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN # 12
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (SECONDS)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 30

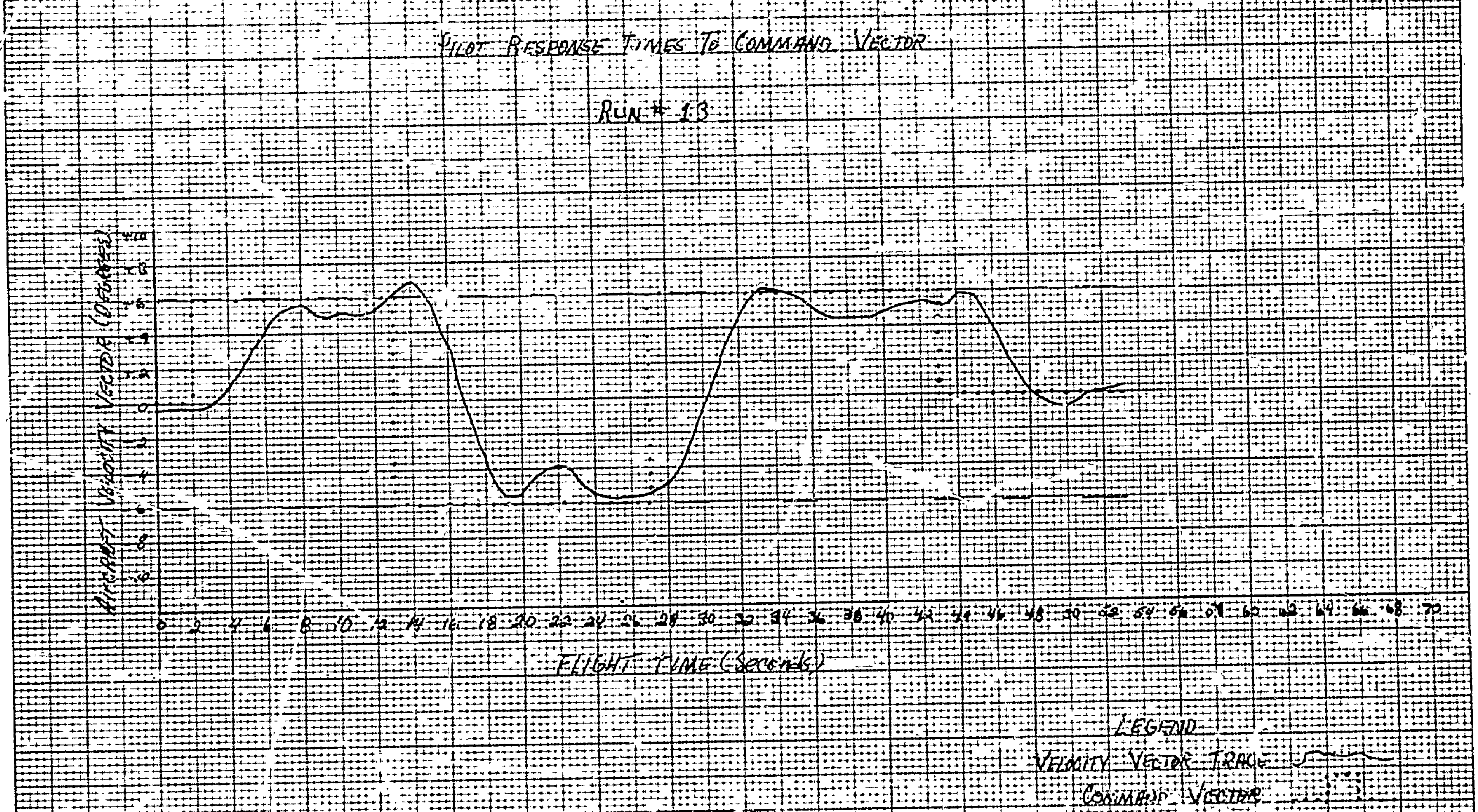
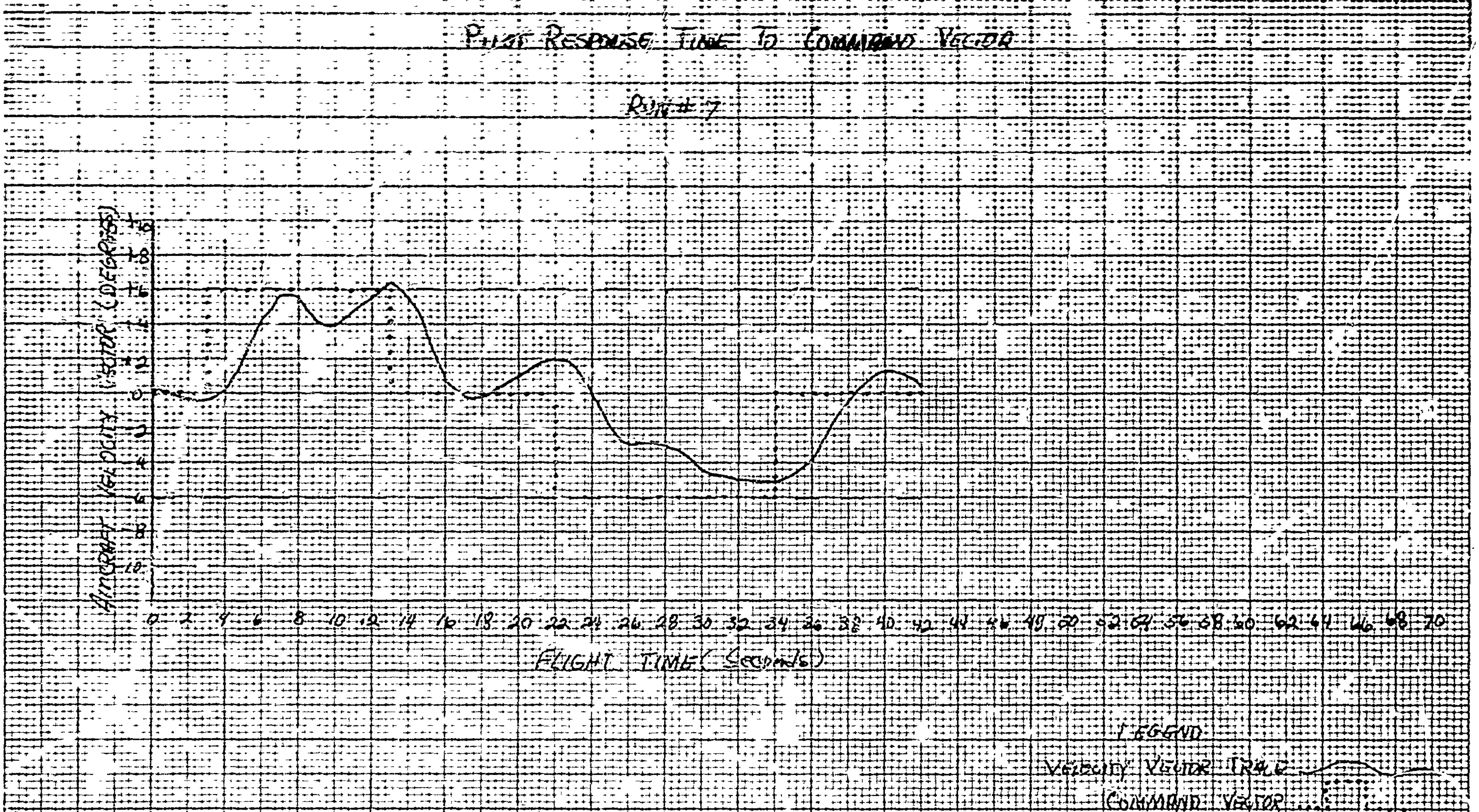

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN # 13
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (Seconds)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 31



PILOT RESPONSE TIME TO COMMAND VECTOR
RUN # 7
AIRCRAFT VELOCITY VECTOR (DEGREES)
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42
FLIGHT TIME (Seconds)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 32

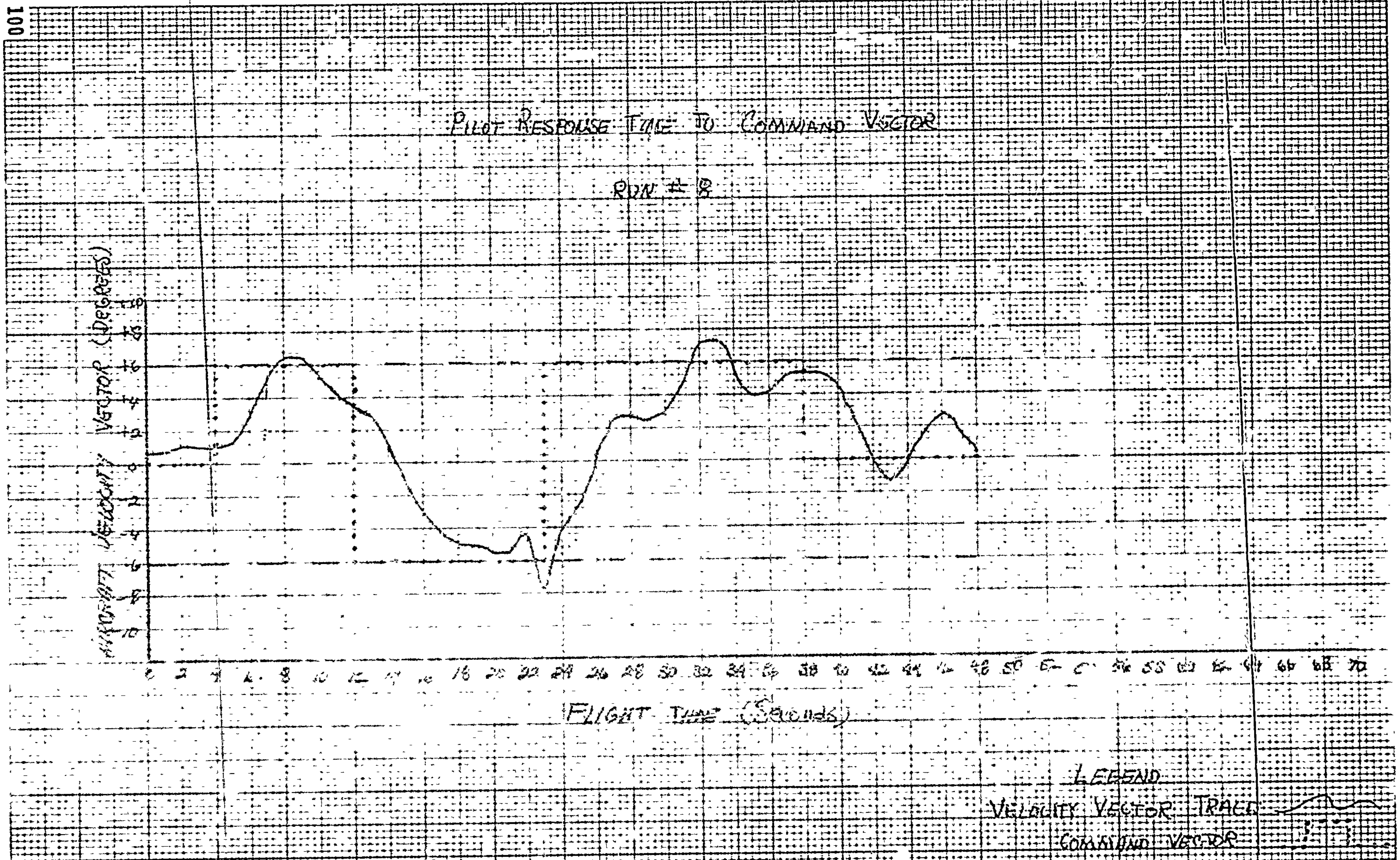
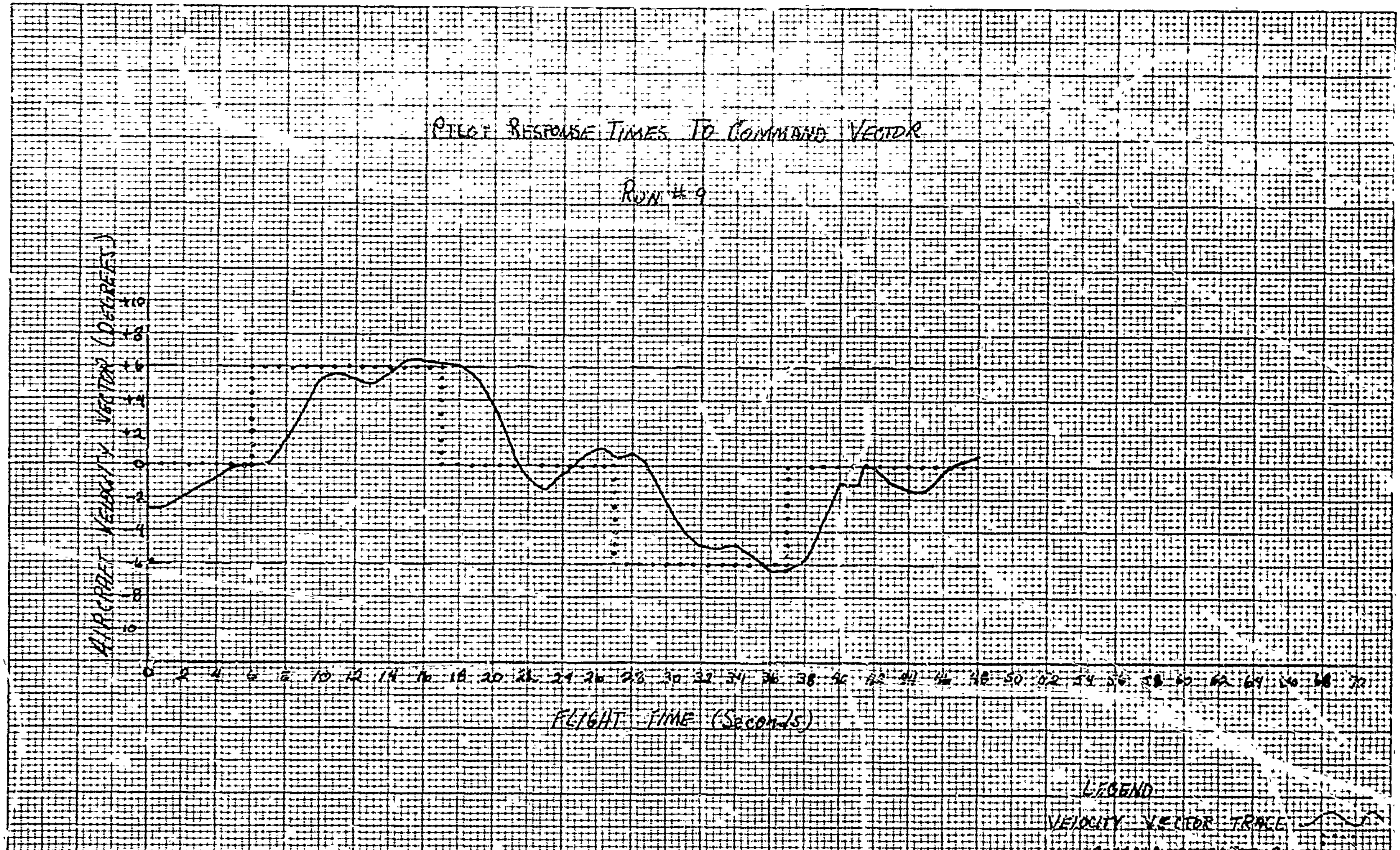

PILOT RESPONSE TIME TO COMMAND VECTOR
RUN # 8
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (SECONDS)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 33



PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN #9
AIRCRAFT VELOCITY VECTOR (DEGREES)
+10
+8
+6
+4
+2
0
-2
-4
-6
-8
-10
FLIGHT TIME (Seconds)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 34

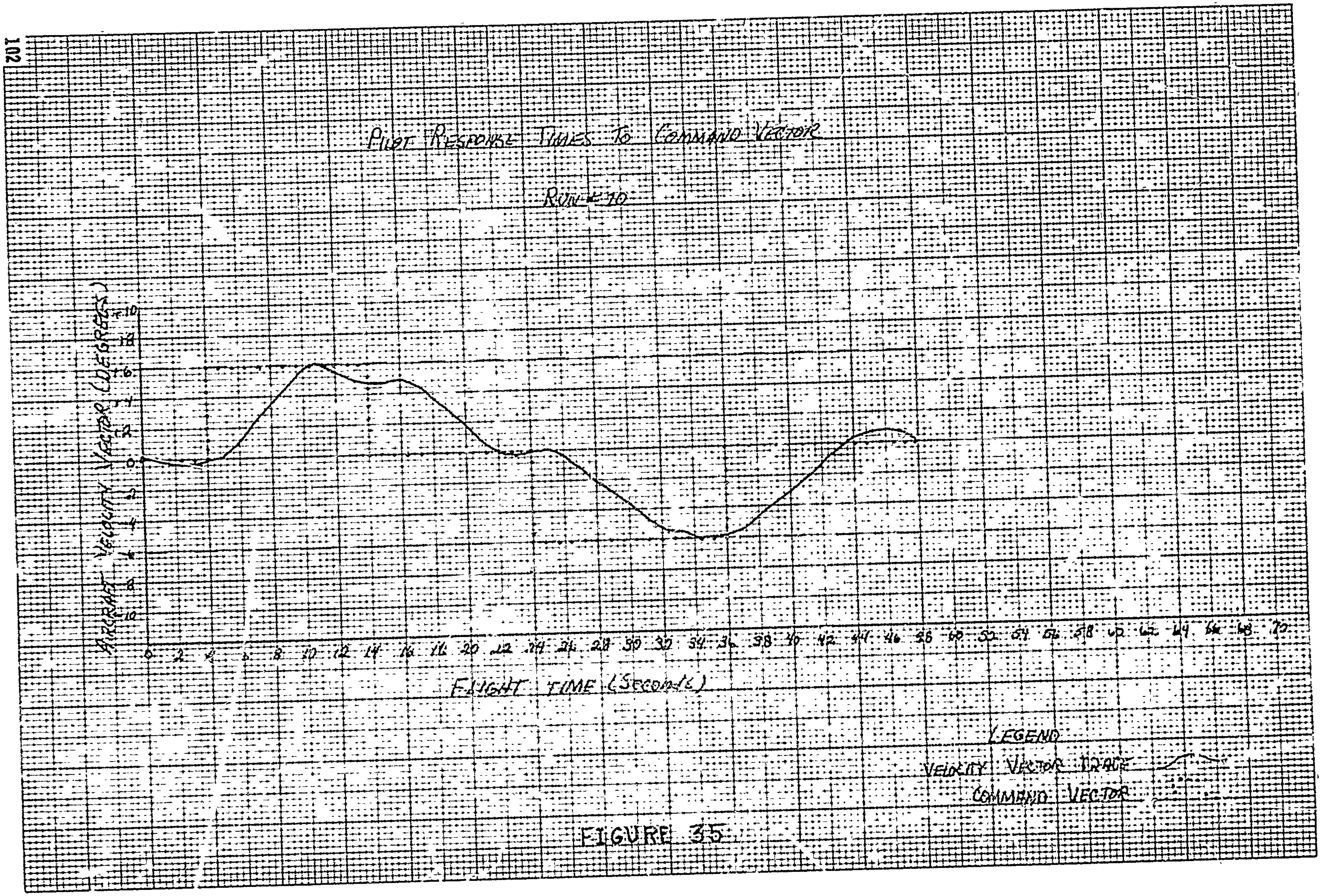

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN #10
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (SECONDS)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 35

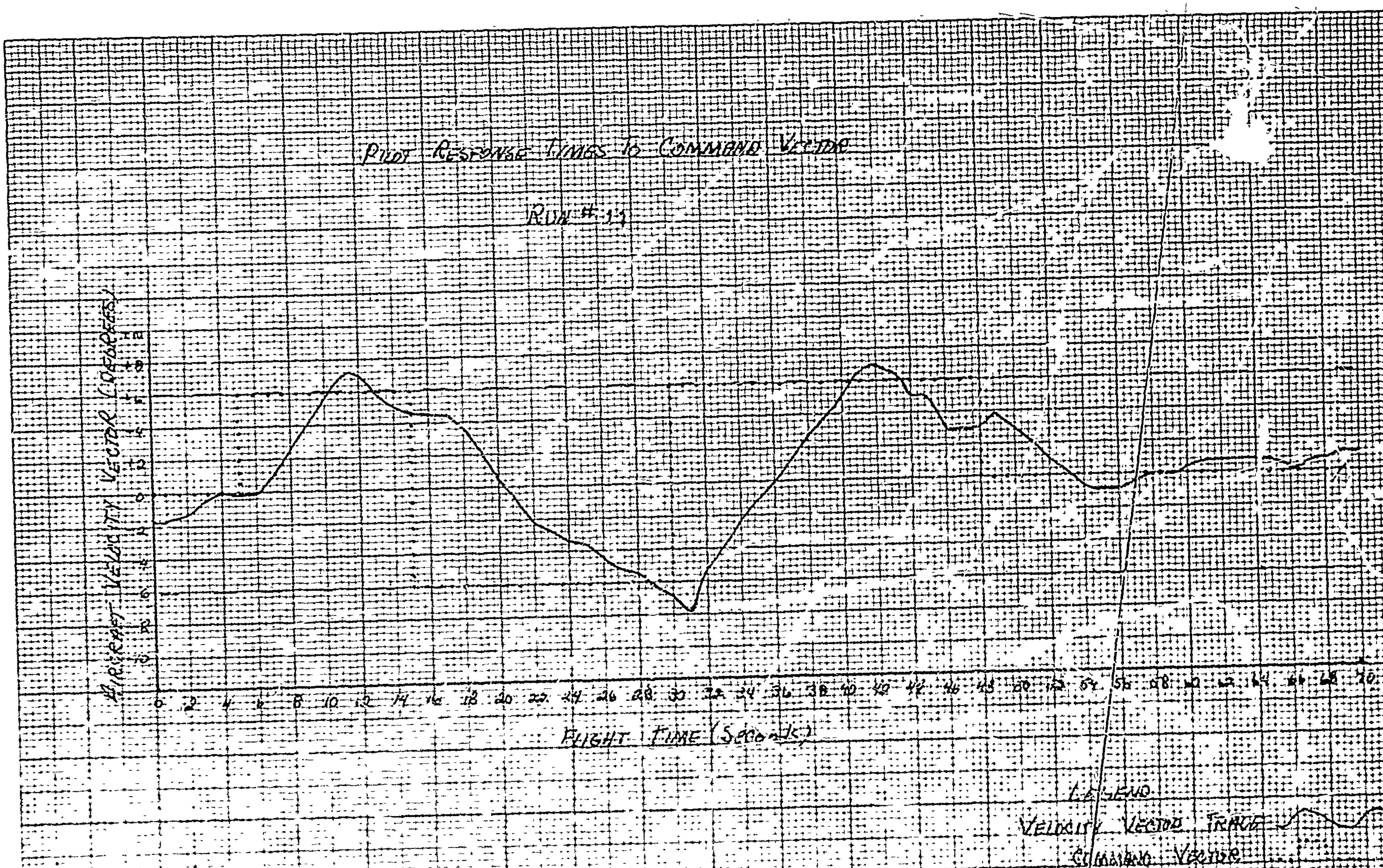

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN # 11
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (SECONDS)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 36

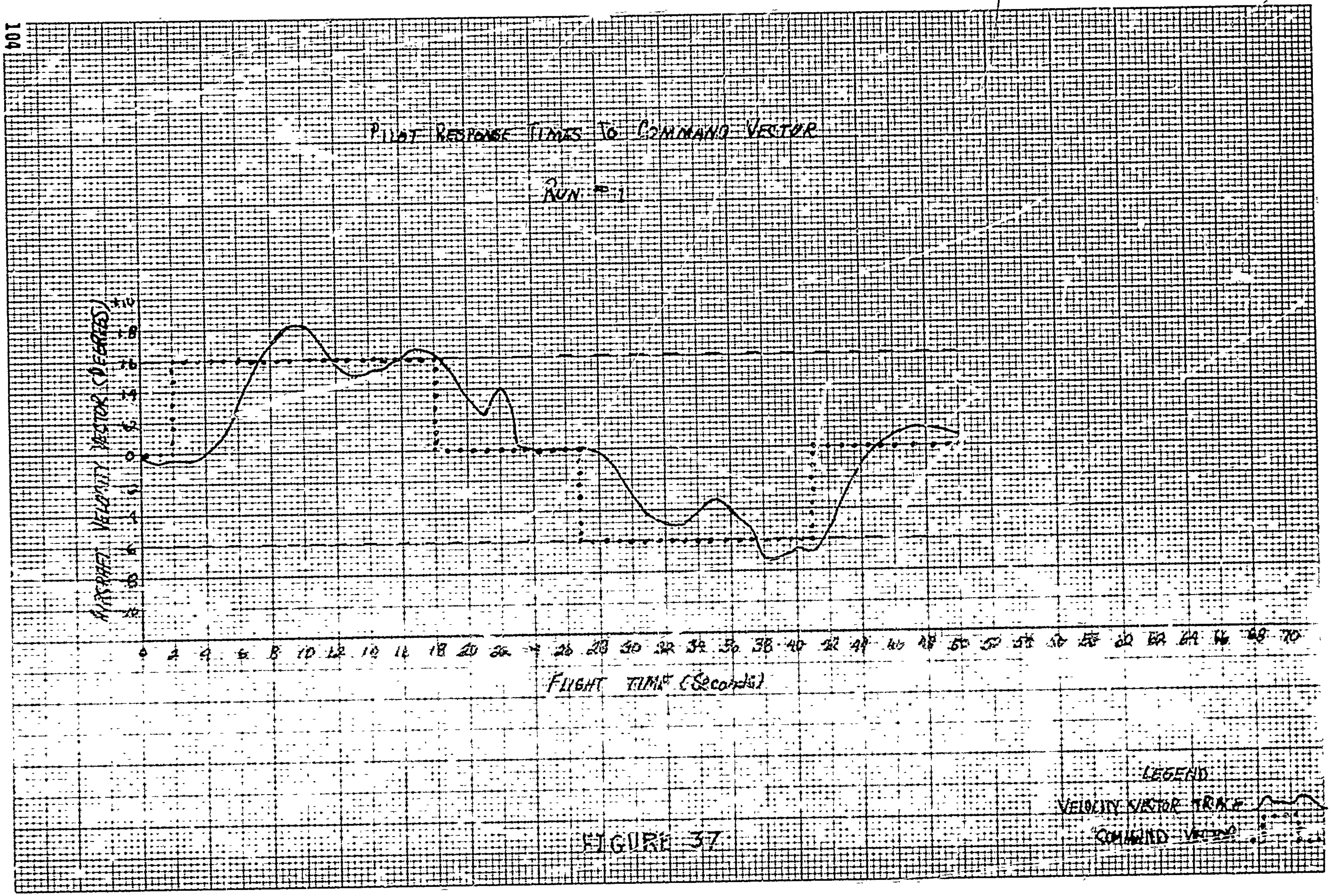

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN #1
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (Seconds)
LEGEND
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 37

PILOT RESPONSE TIMES TO COMMAND VECTOR

RUN #2

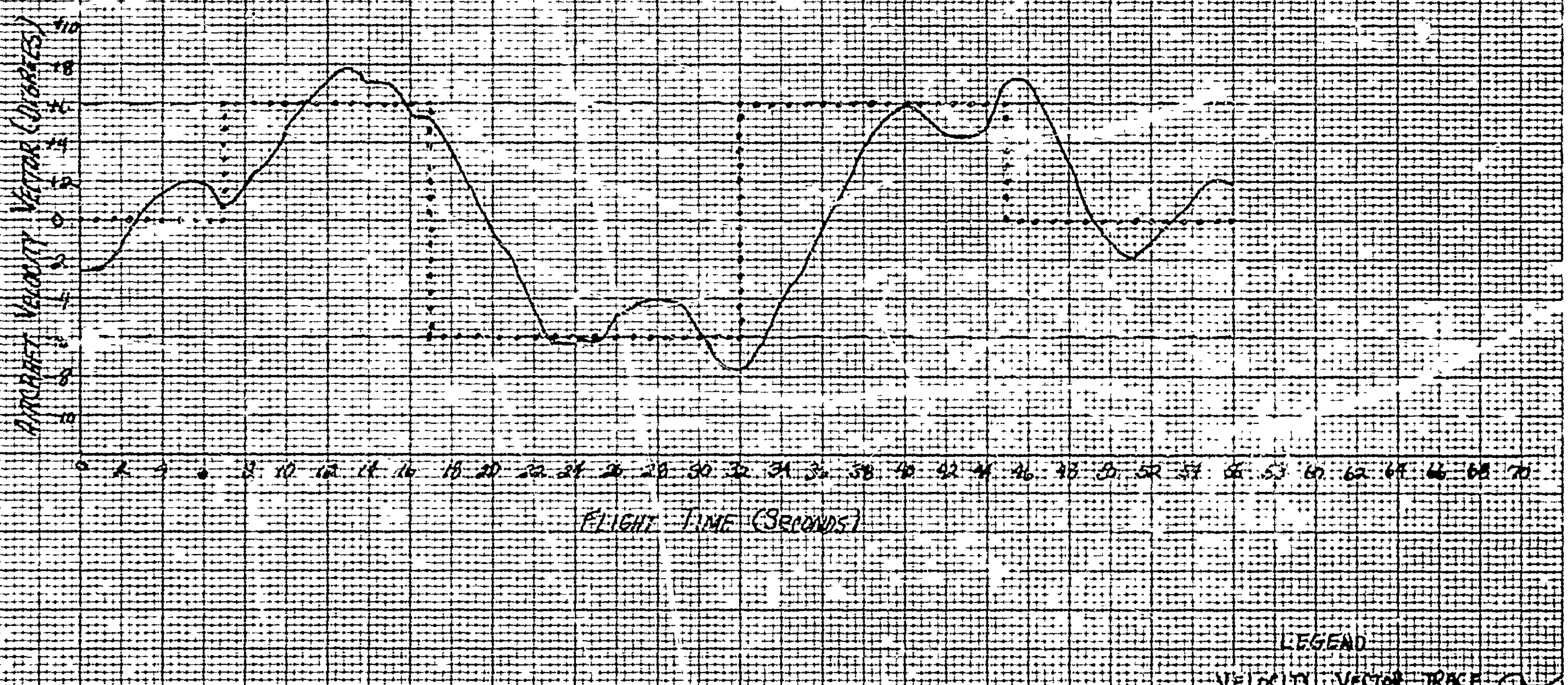


FIGURE 38

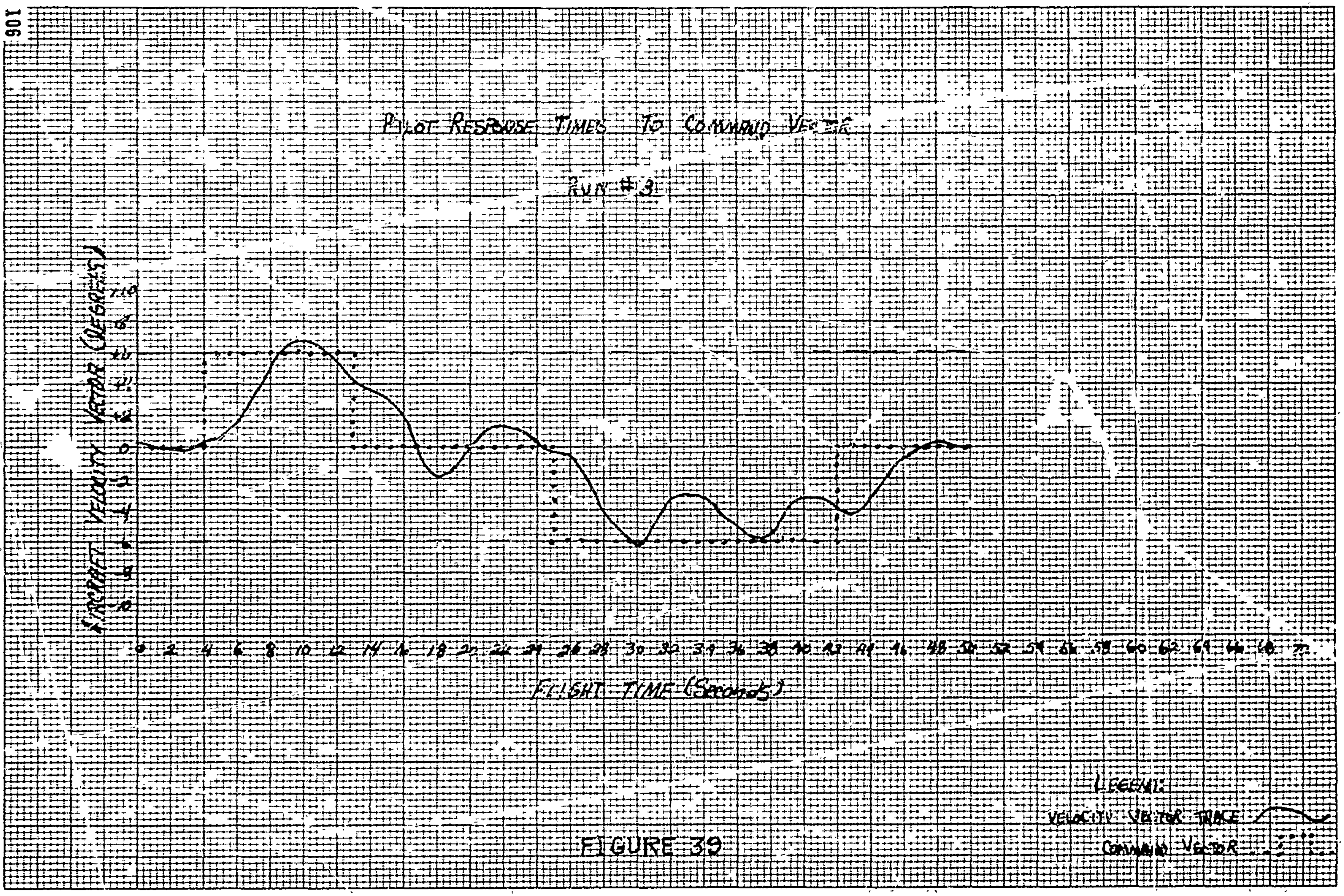

PILOT RESPONSE TIMES TO COMMAND VECTOR
RUN #3
AIRCRAFT VELOCITY VECTOR (DEGREES)
FLIGHT TIME (Seconds)
LEGEND:
VELOCITY VECTOR TRACE
COMMAND VECTOR

FIGURE 39

PILOT RESPONSE TIMES TO COMMAND VECTOR

RUN # 4

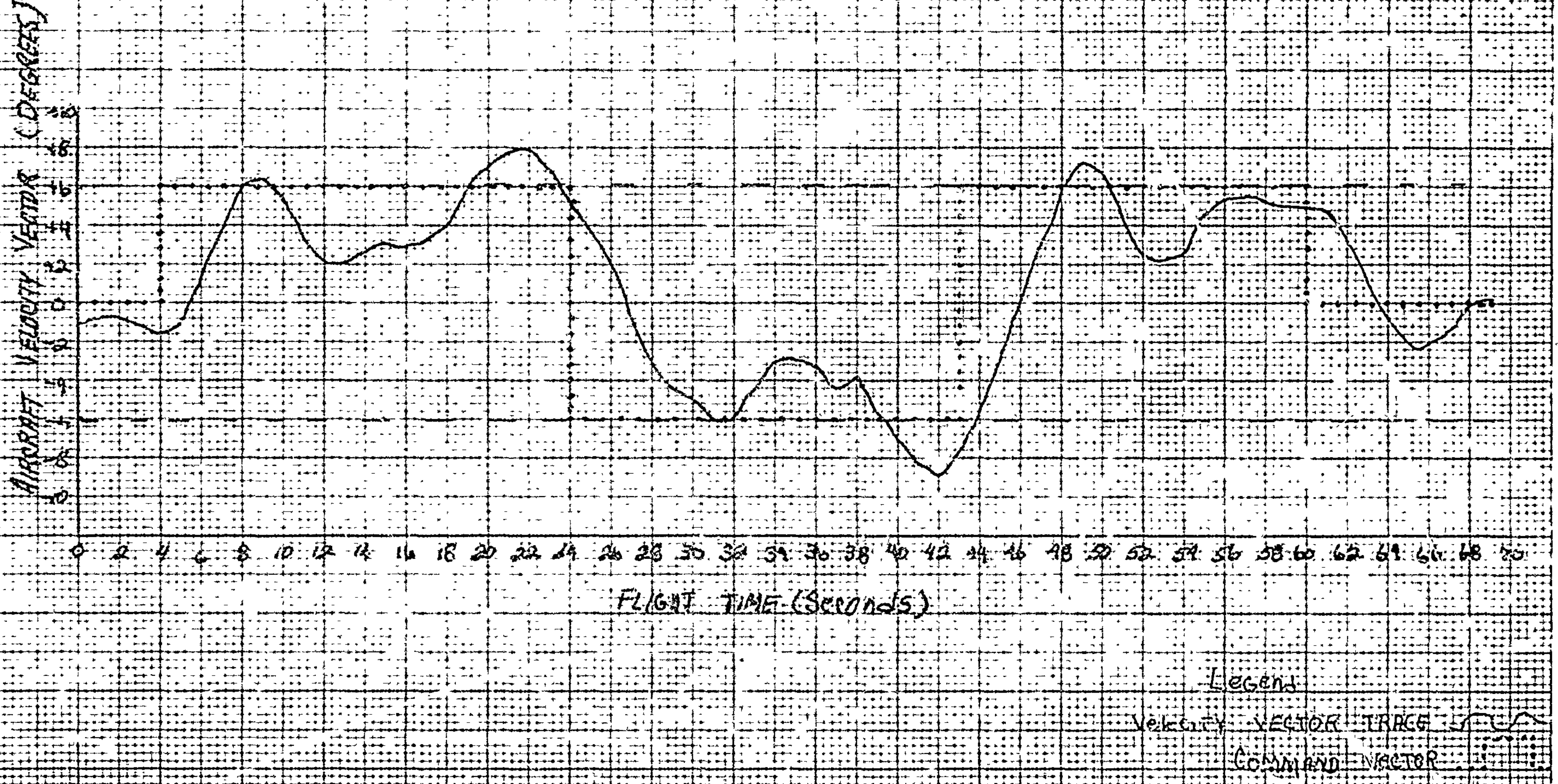
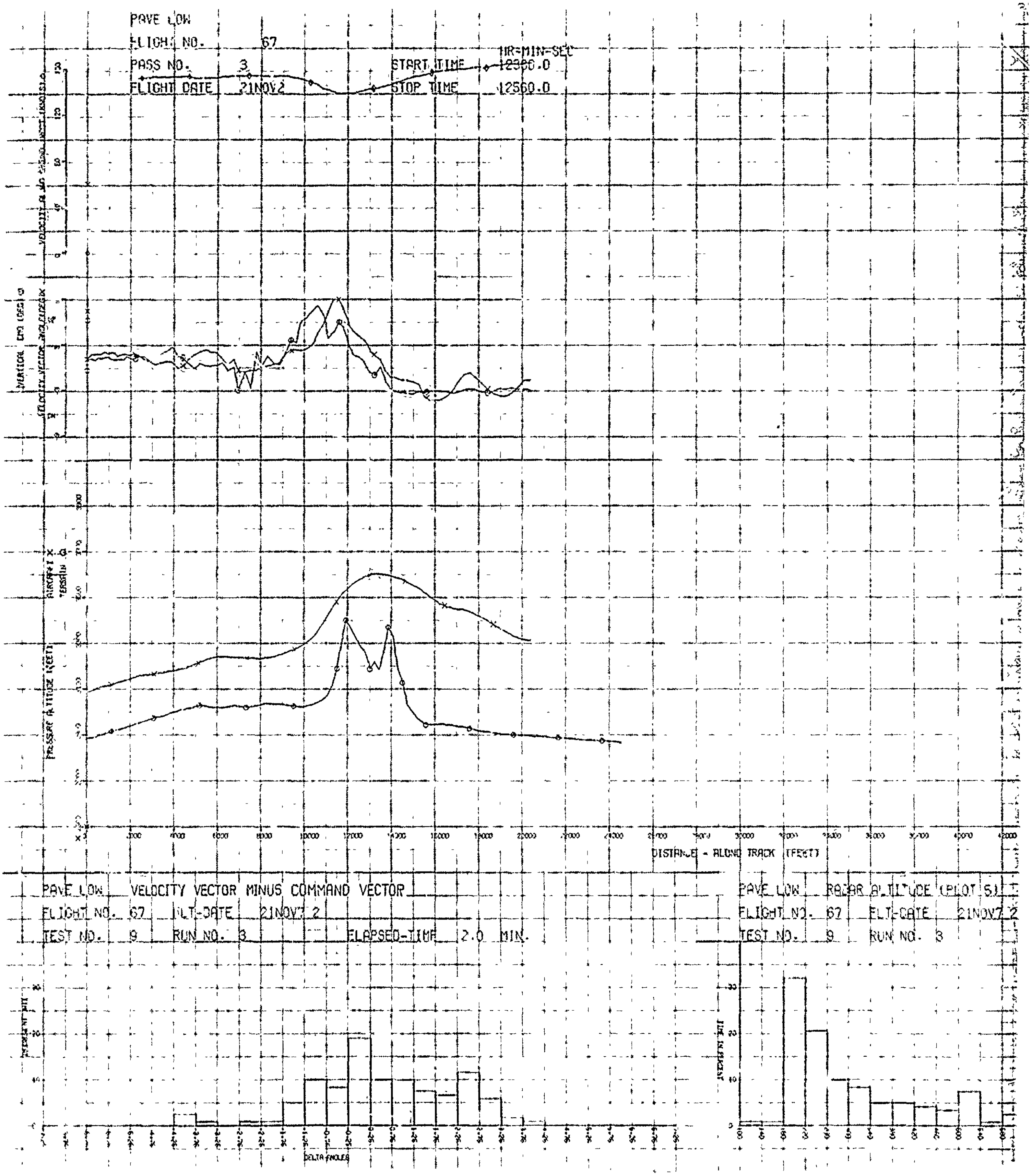


FIGURE 40

Table I

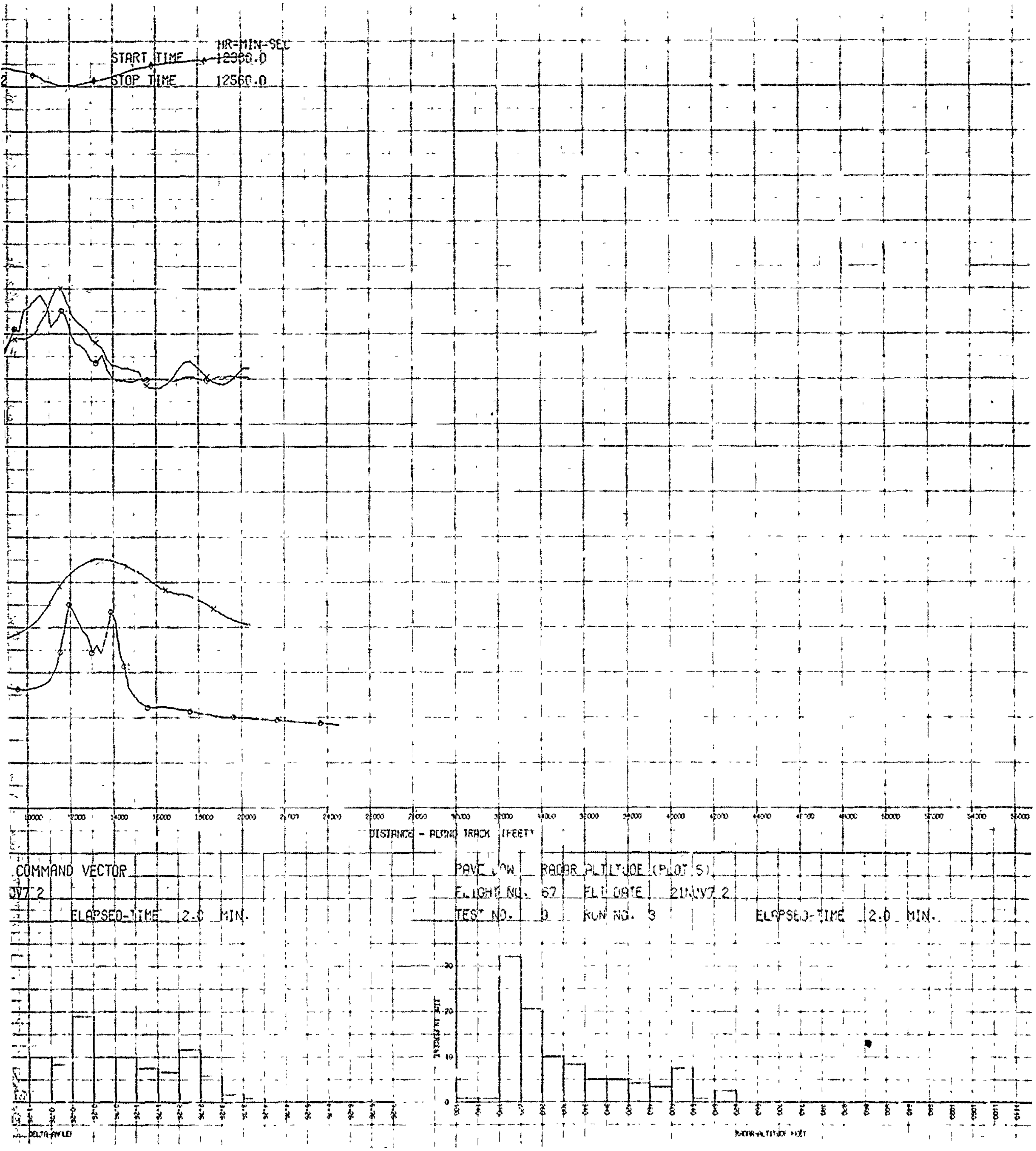
PILOT RESPONSE TIMES TO COMMAND VECTOR SUMMARY

Appendix III Figure No.	Pilot	Response Time (sec)					
		To Pullup Command			To Pushover Command		
		0° to +6°	-6° to 0°	-6° to +6°	0° to -6°	+6° to 0°	+6° to -6°
28	AFFTC	4.2	3.4		6.9	5.9	
29	Primary	5.1		6.0		6.1	5.2
30	Test	5.0	4.0		7.4	4.2	
31	Pilot	6.0		6.2		5.9	6.1
32	AFFTC	4.0	5.2		8.6	3.6	
33	Alternate	4.4		7.3		4.5	10.0
34	Test Pilot No. 1	8.5	4.1		8.0	4.3	
35	AFFTC Alter-nate	6.3	8.0		11.0	10.0	
36	Test Pilot No. 2	5.2		9.9		10.0	15.0
37	MAC (ARRS)	4.9	3.7		6.0	5.7	
38	Pilot No. 1	4.6		7.0		3.6	6.3
39	MAC (ARRS)	5.9	7.5		4.8	5.4	
40	Pilot No. 2	3.2		4.4		4.3	7.6
Average		5.2	5.1	6.8	7.[illegible]	5.7	8.4



NOMINAL GROUND SPEED 150KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

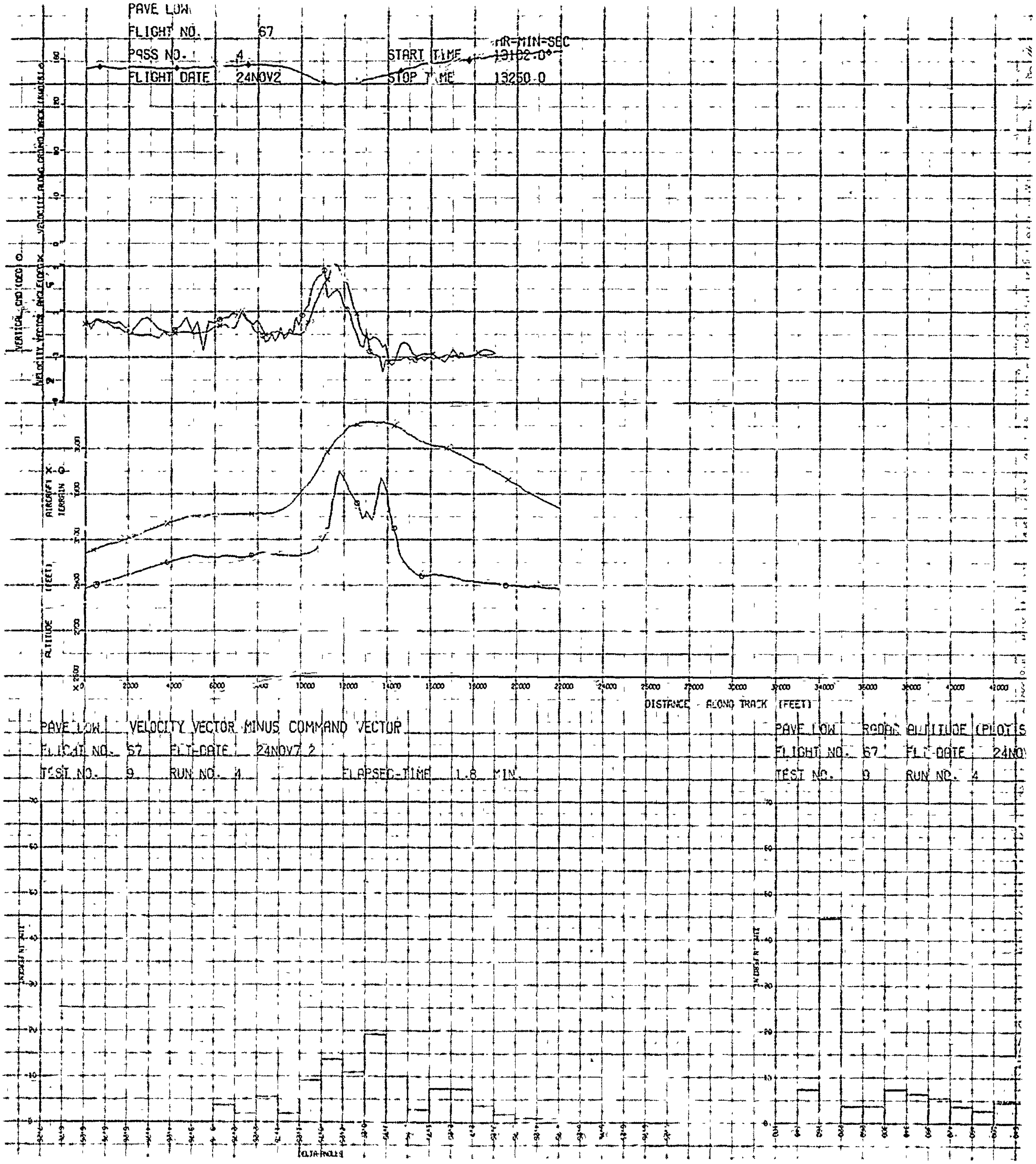
FIGURE 41



NOMINAL GROUND SPEED 150KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

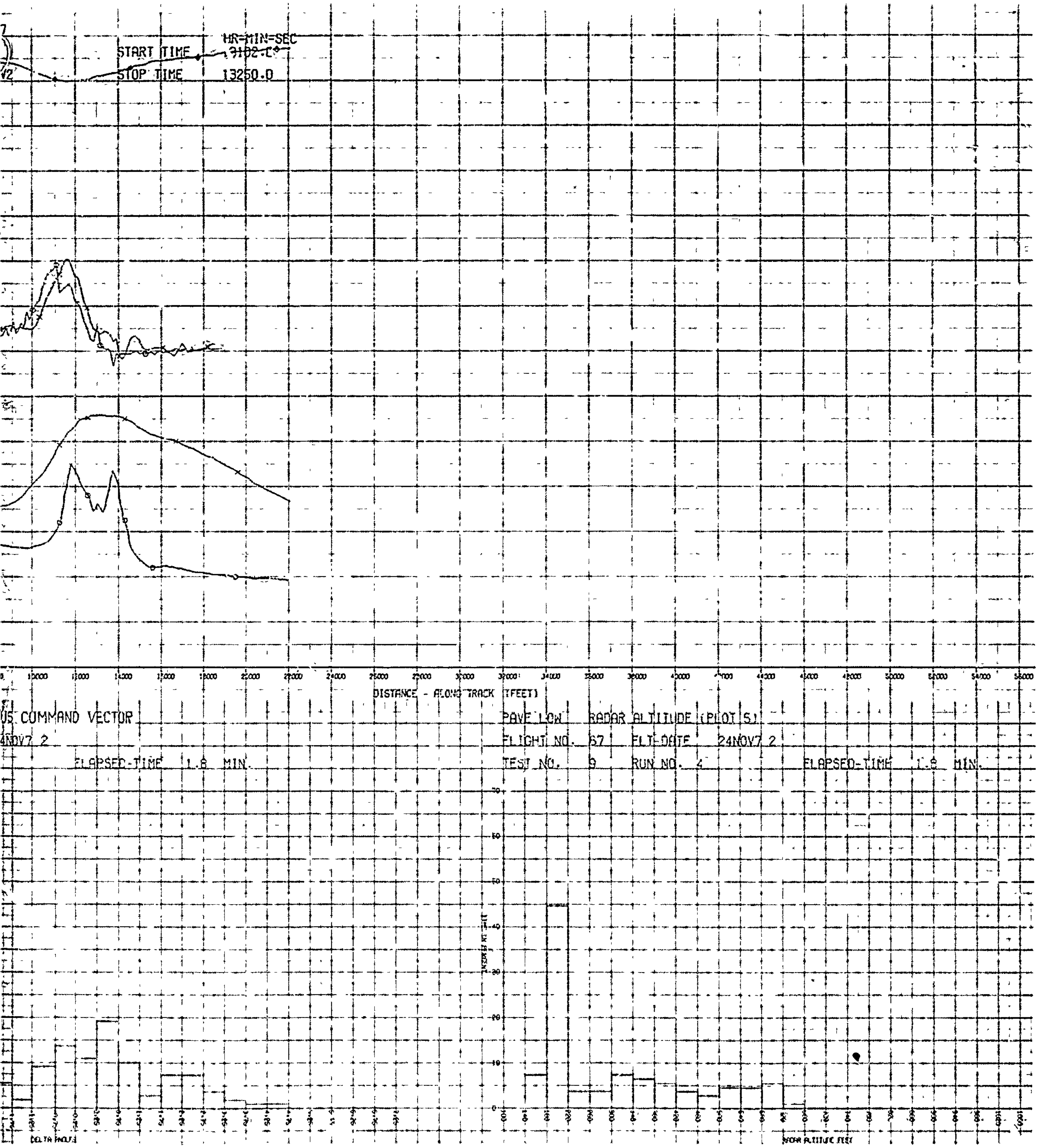
FIGURE 41

2



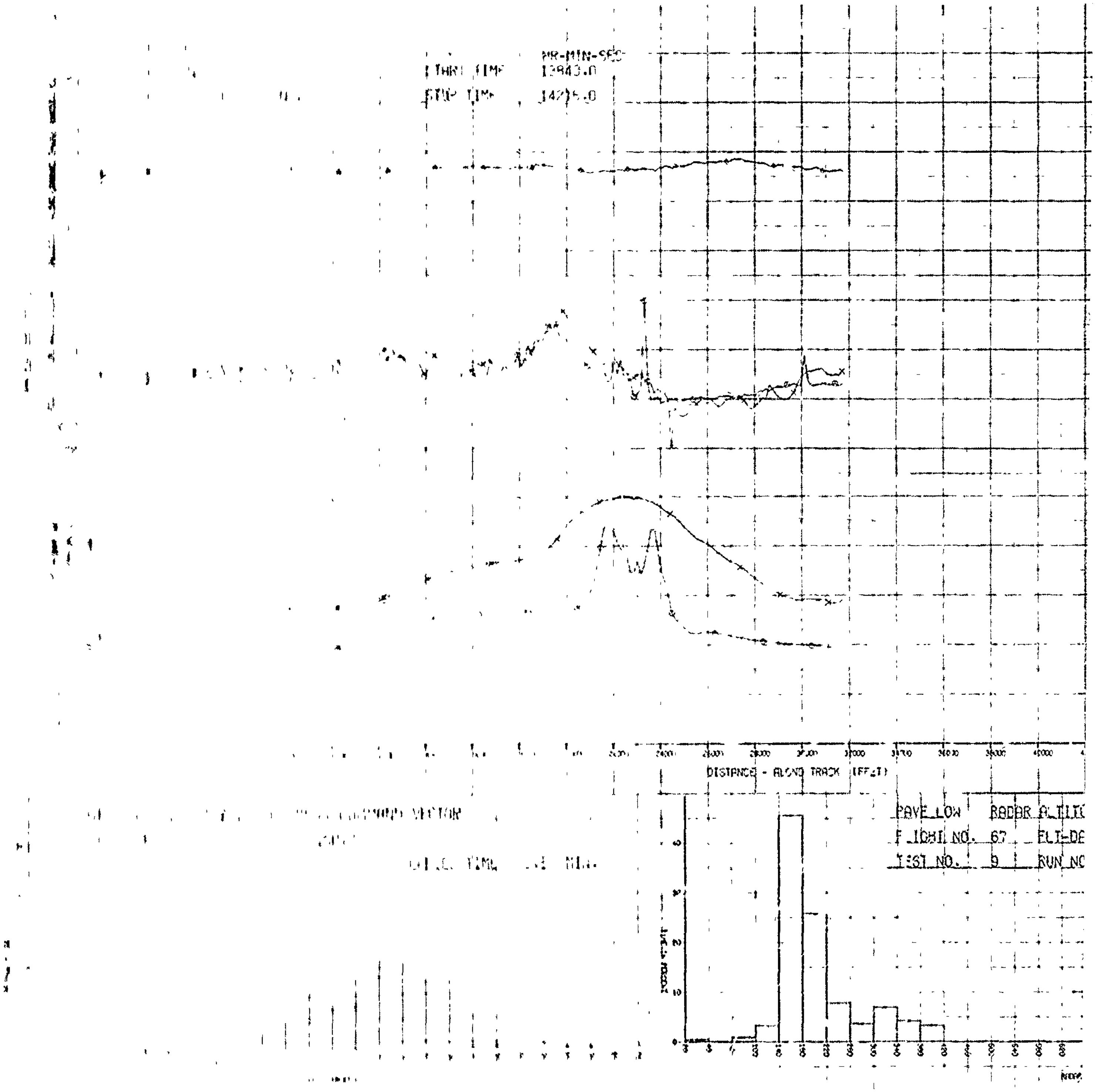
NOMINAL GROUND SPEED 150KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 42



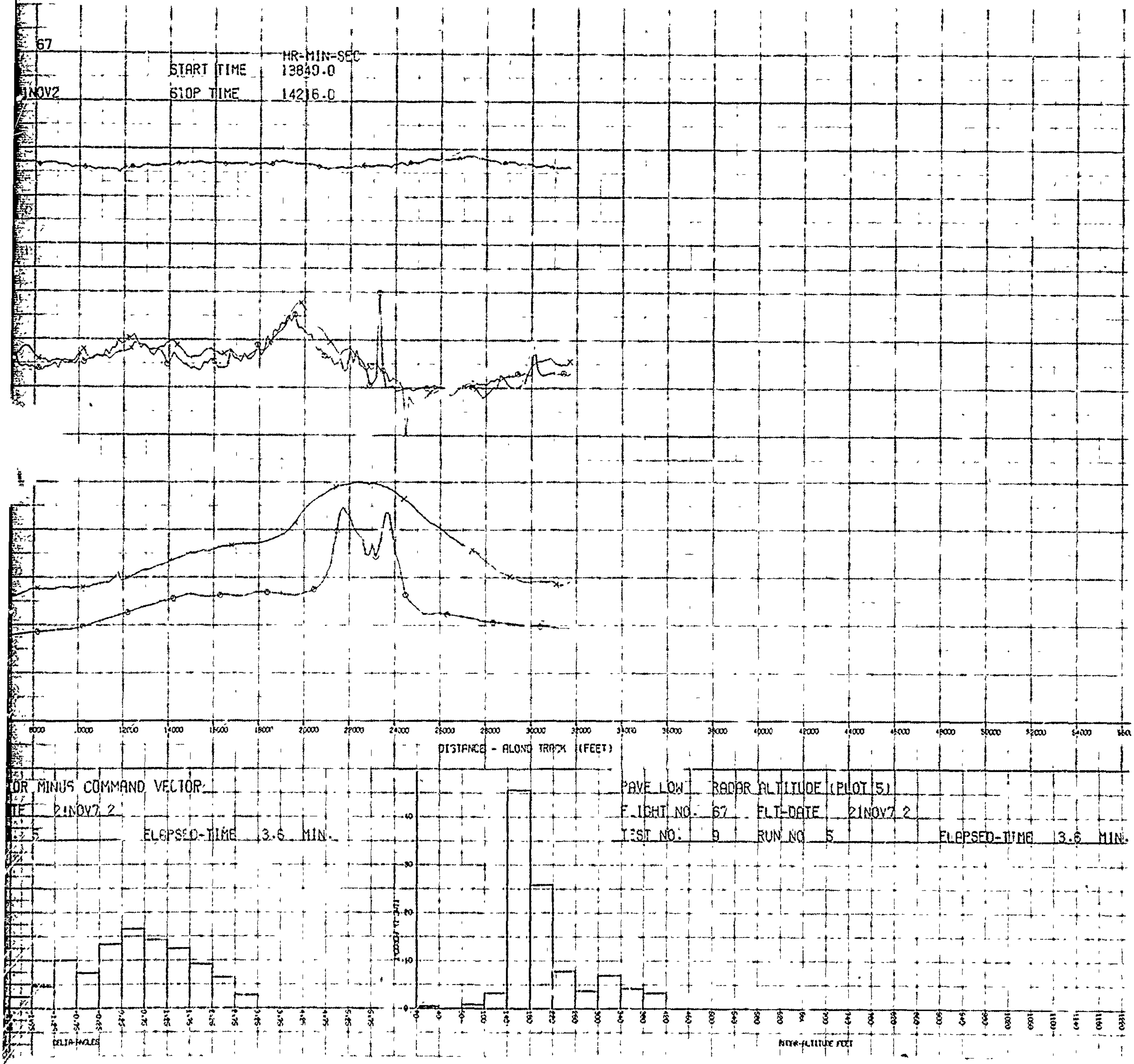
NOMINAL GROUND SPEED 150KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 42



NOMINAL GROUND SPEED 80KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

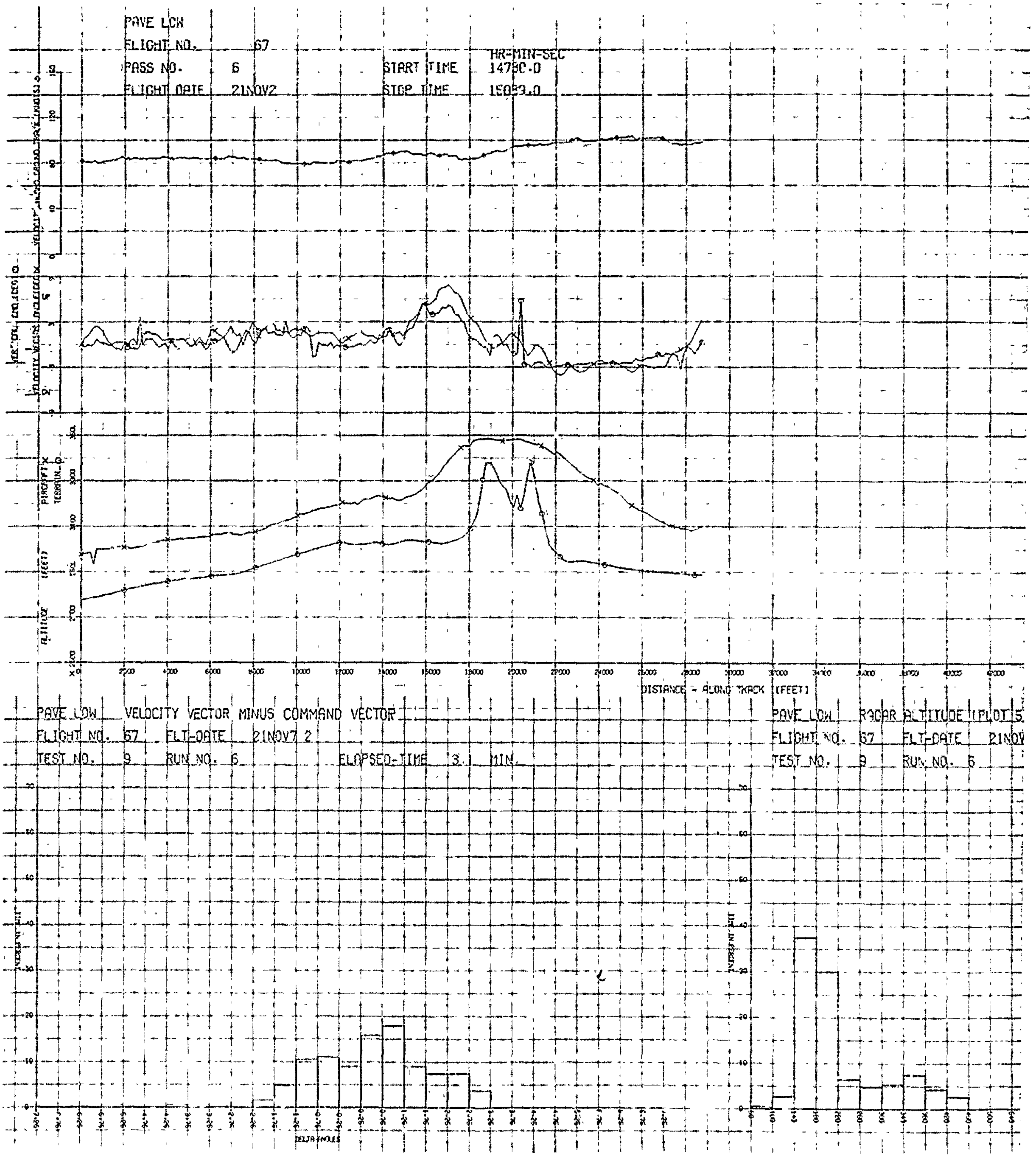
FIGURE 43



NOMINAL GROUND SPEED 80KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

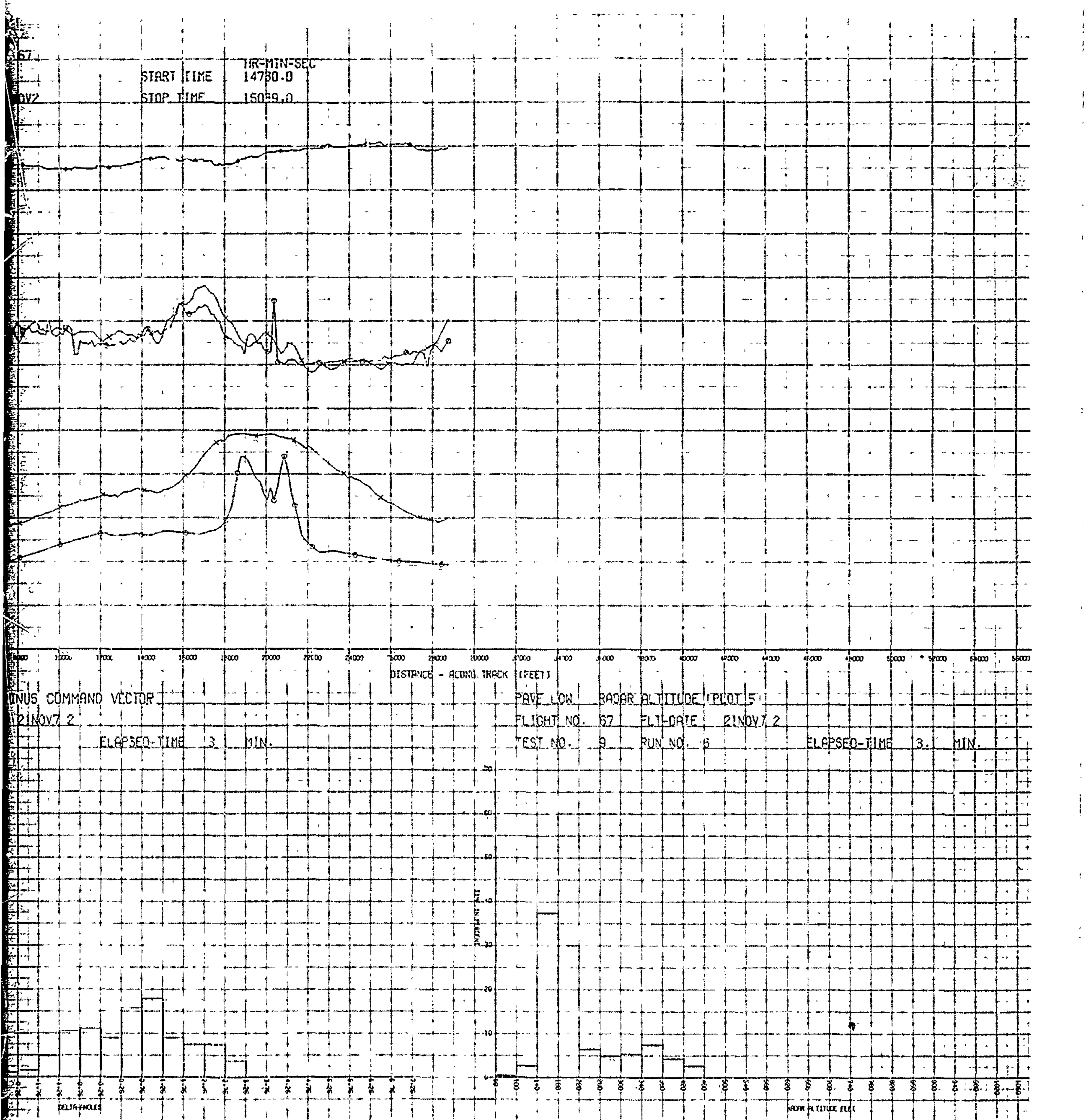
FIGURE 43

2



NOMINAL GROUND SPEED 80KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 44



NOMINAL GROUND SPEED 80KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND ON

FIGURE 44

2

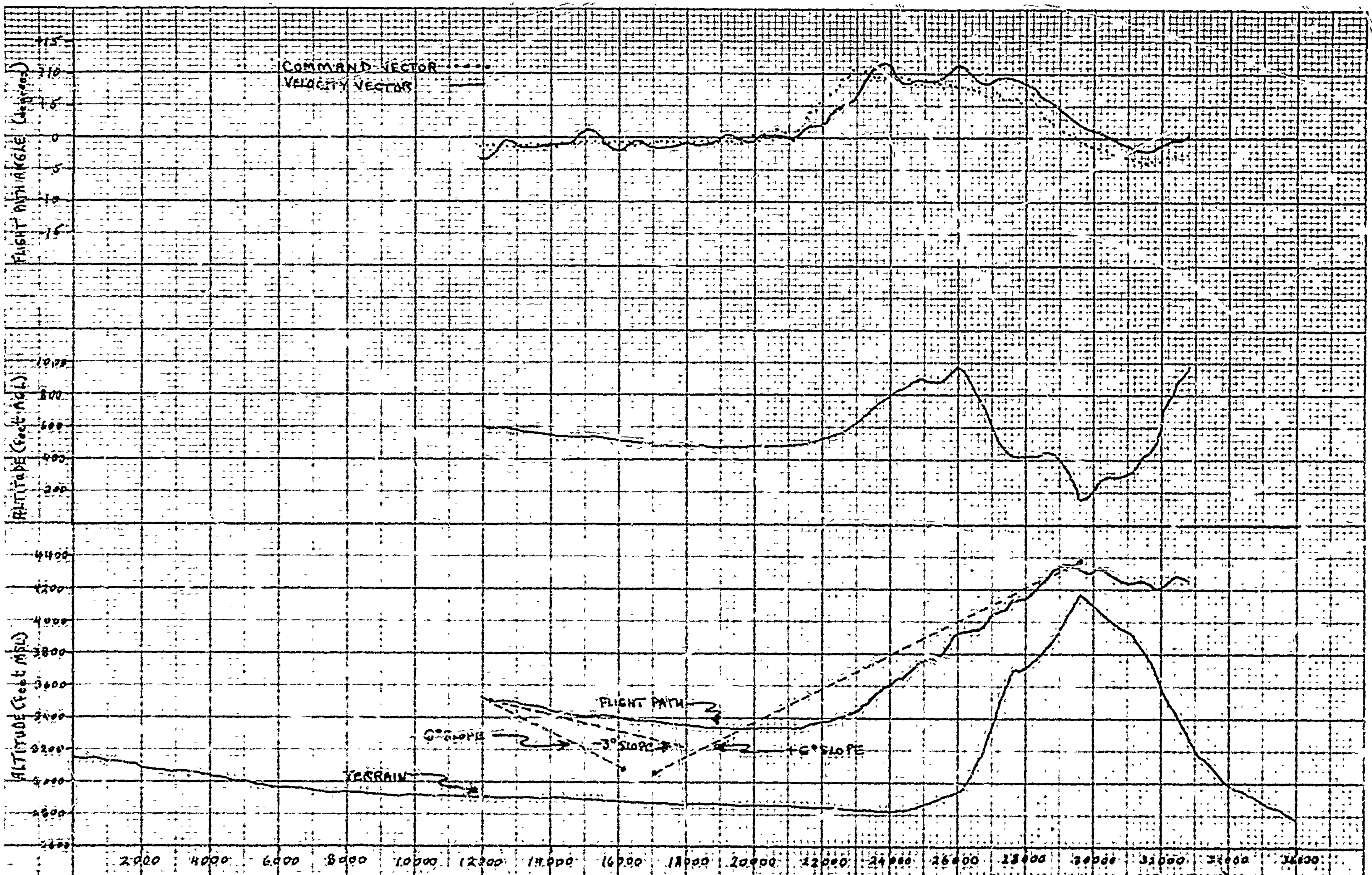


FIGURE 45 DESCENT TO TF FLIGHT, NO. 1

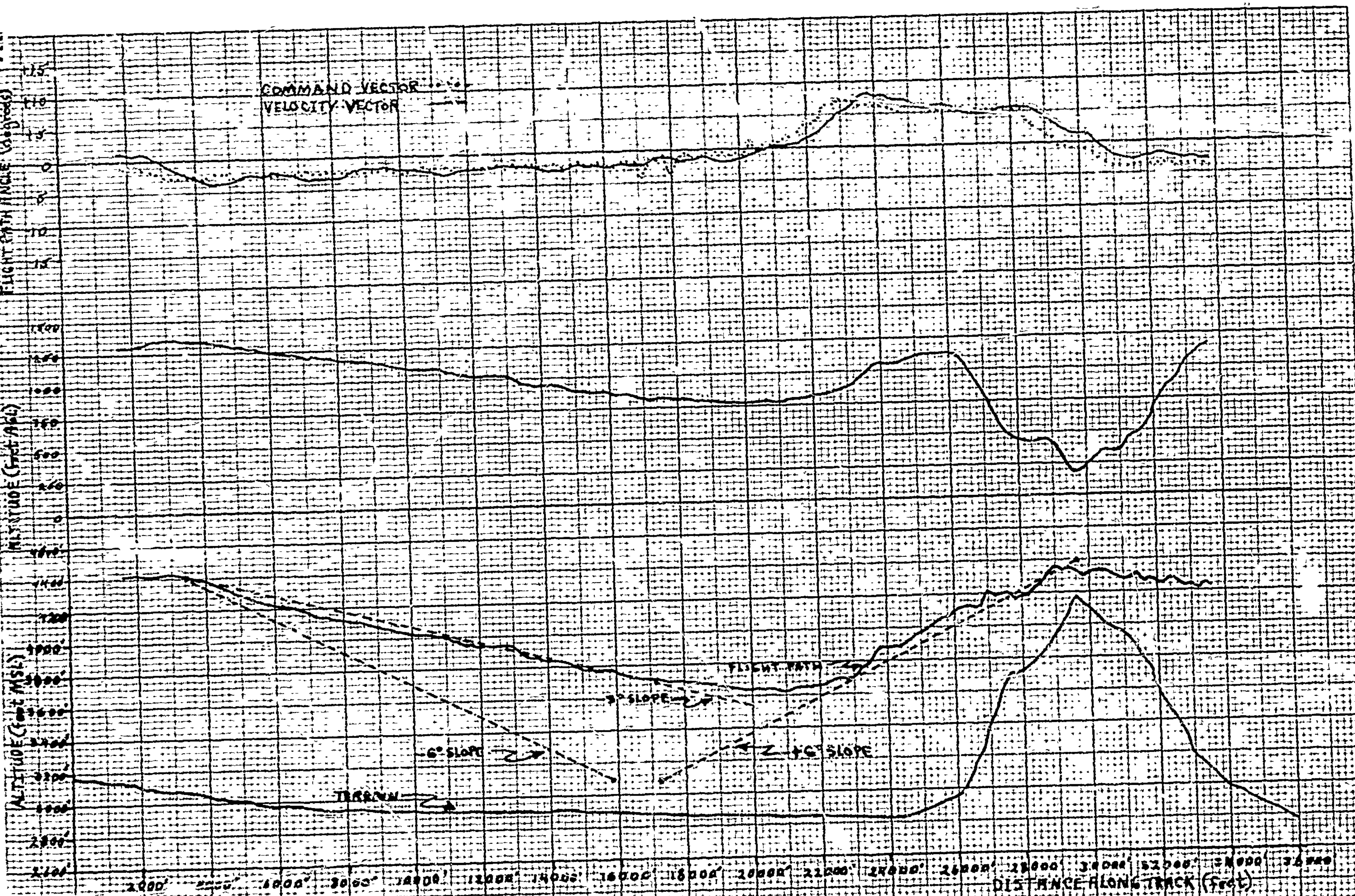


FIGURE 46 DESCENT TO TF FLIGHT, NO. 2.

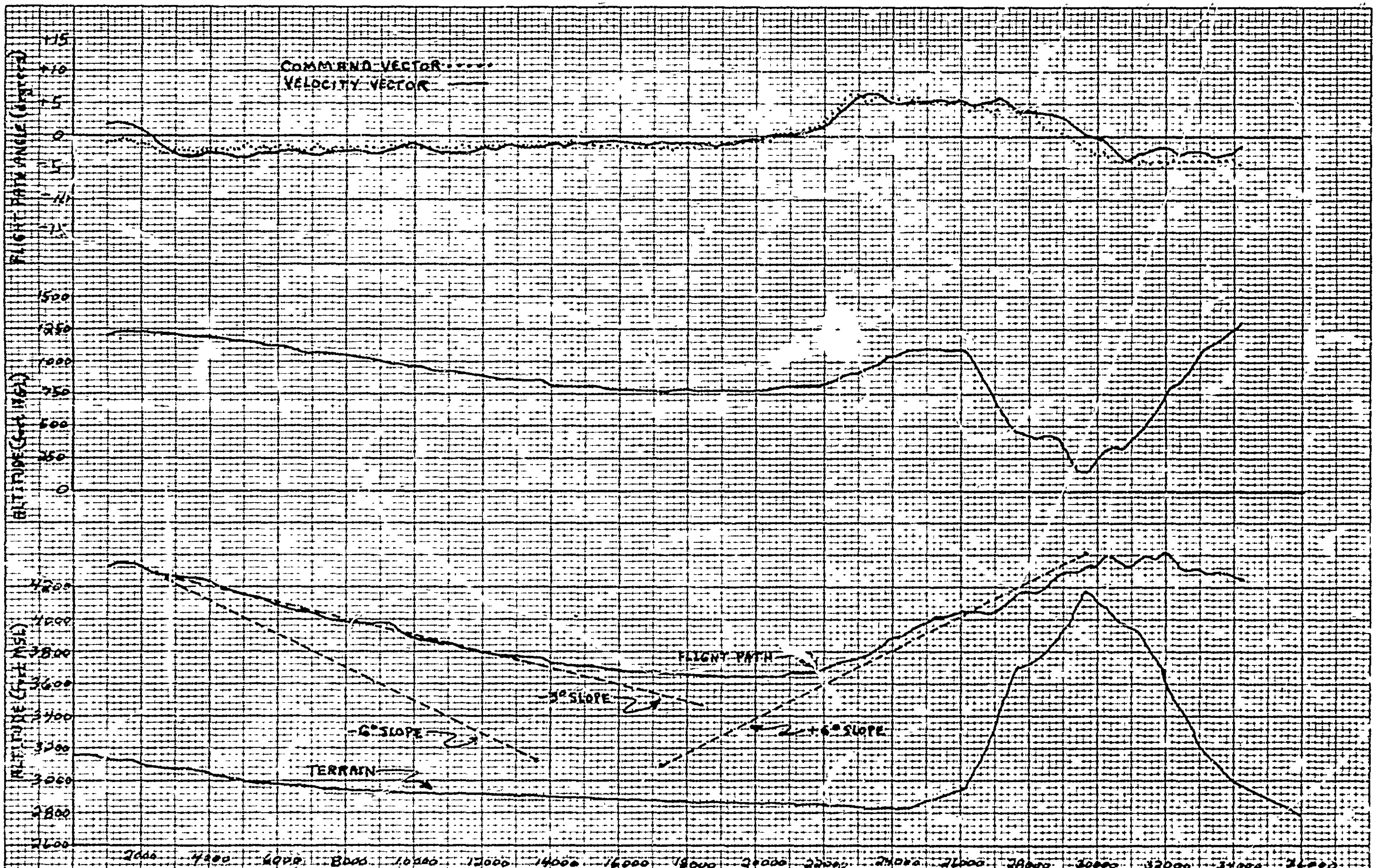
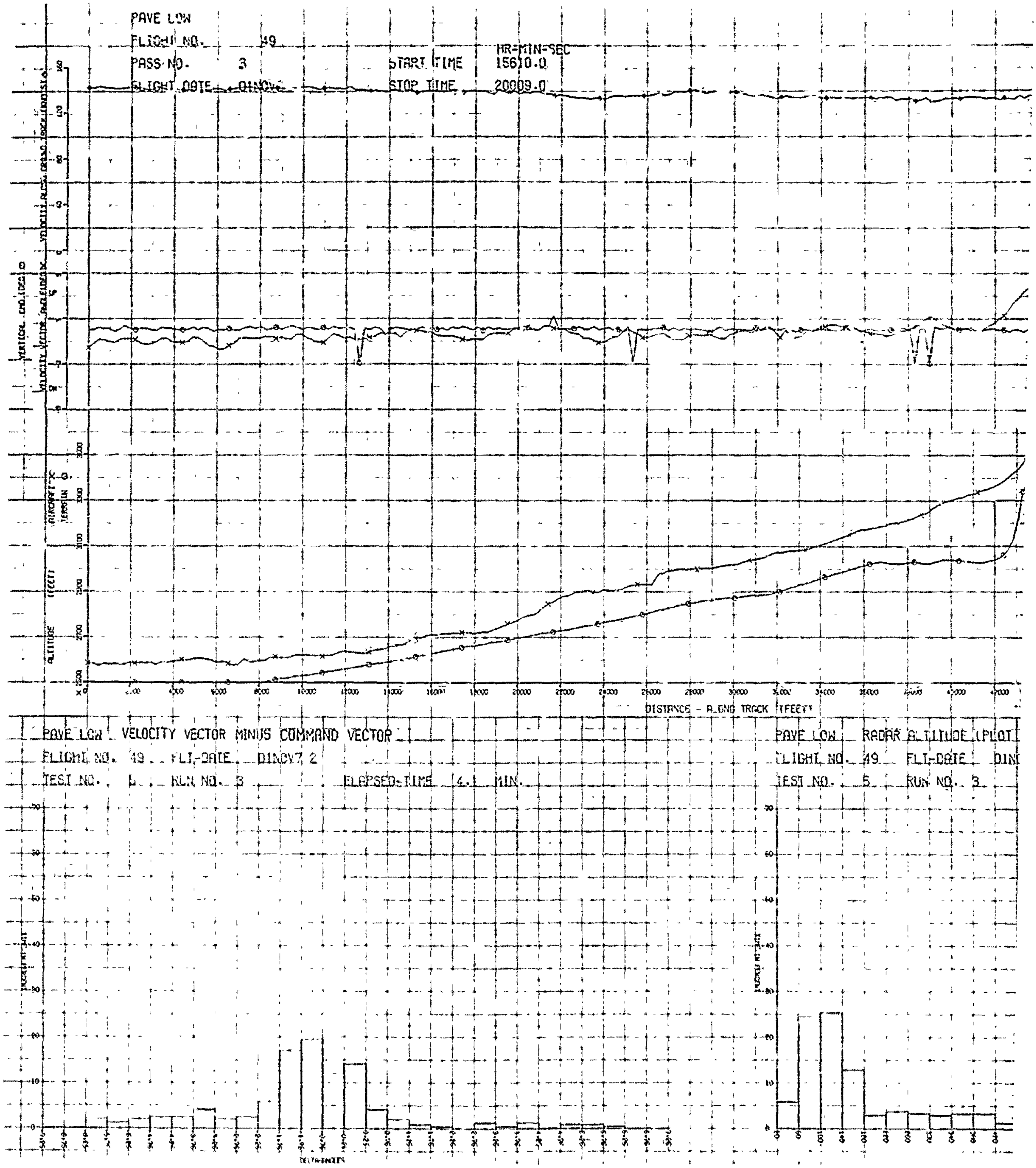
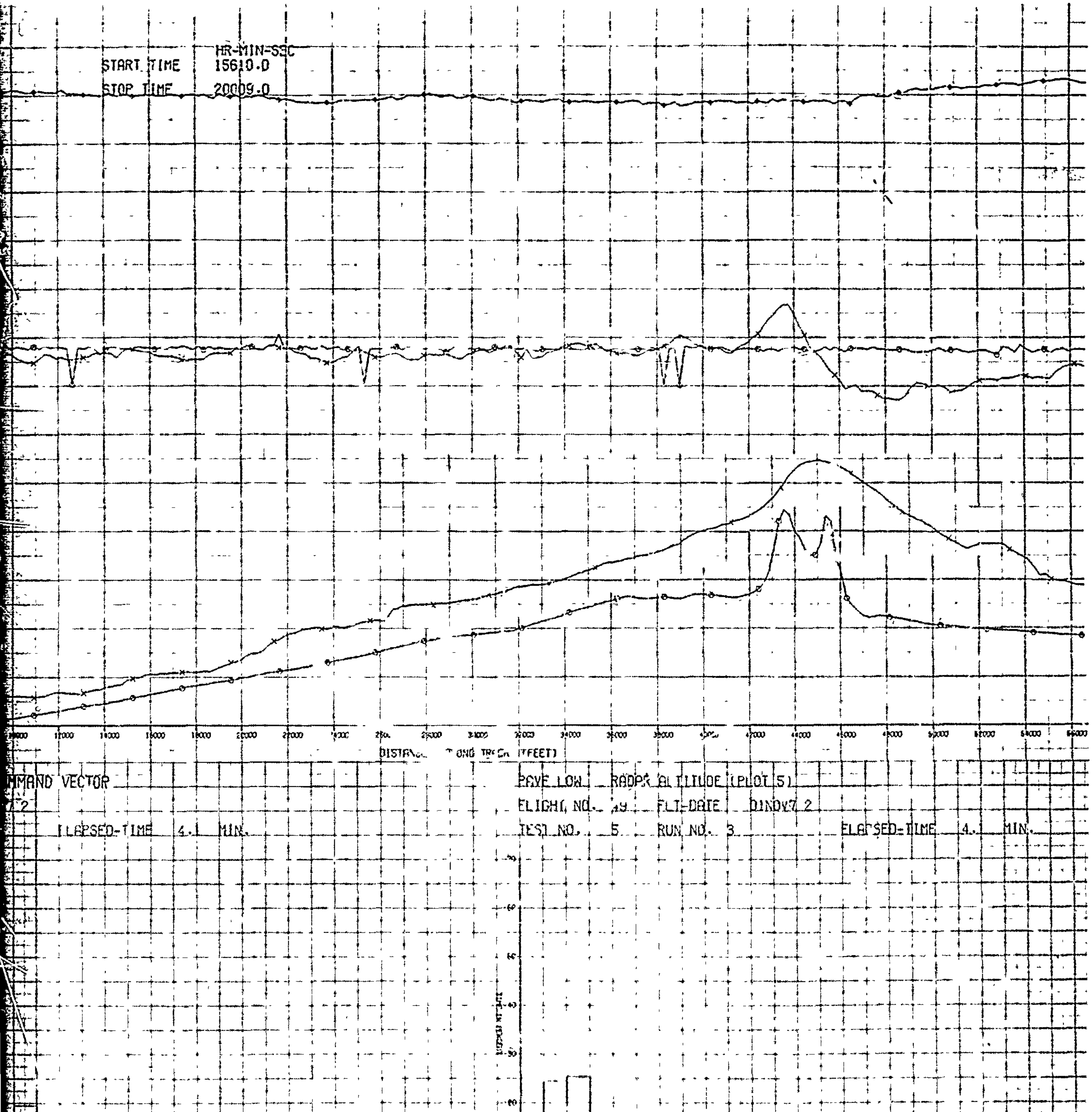


FIGURE 47 DESCENT TO TF FLIGHT, NO. 3



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND OFF

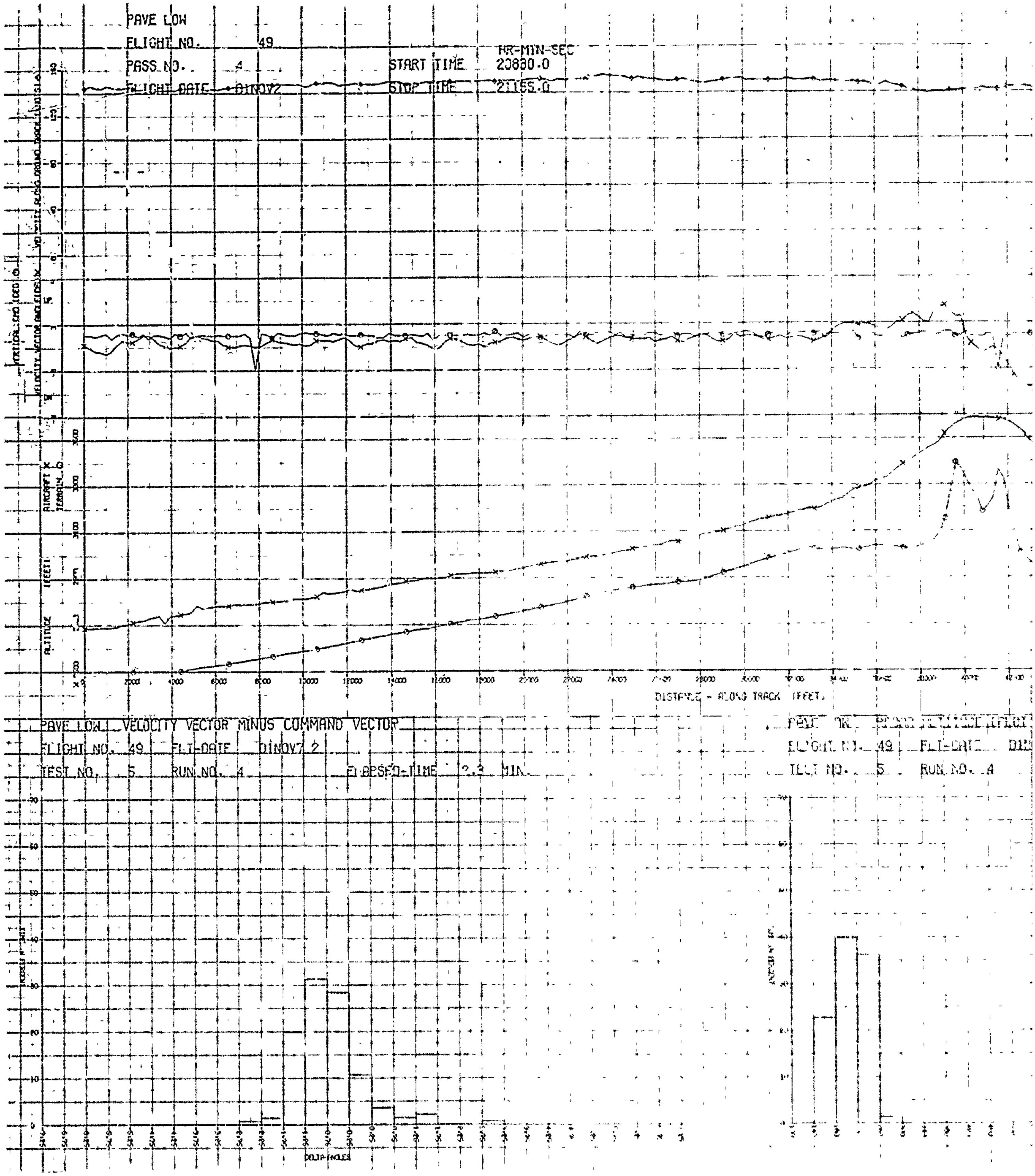
FIGURE 48



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND OFF

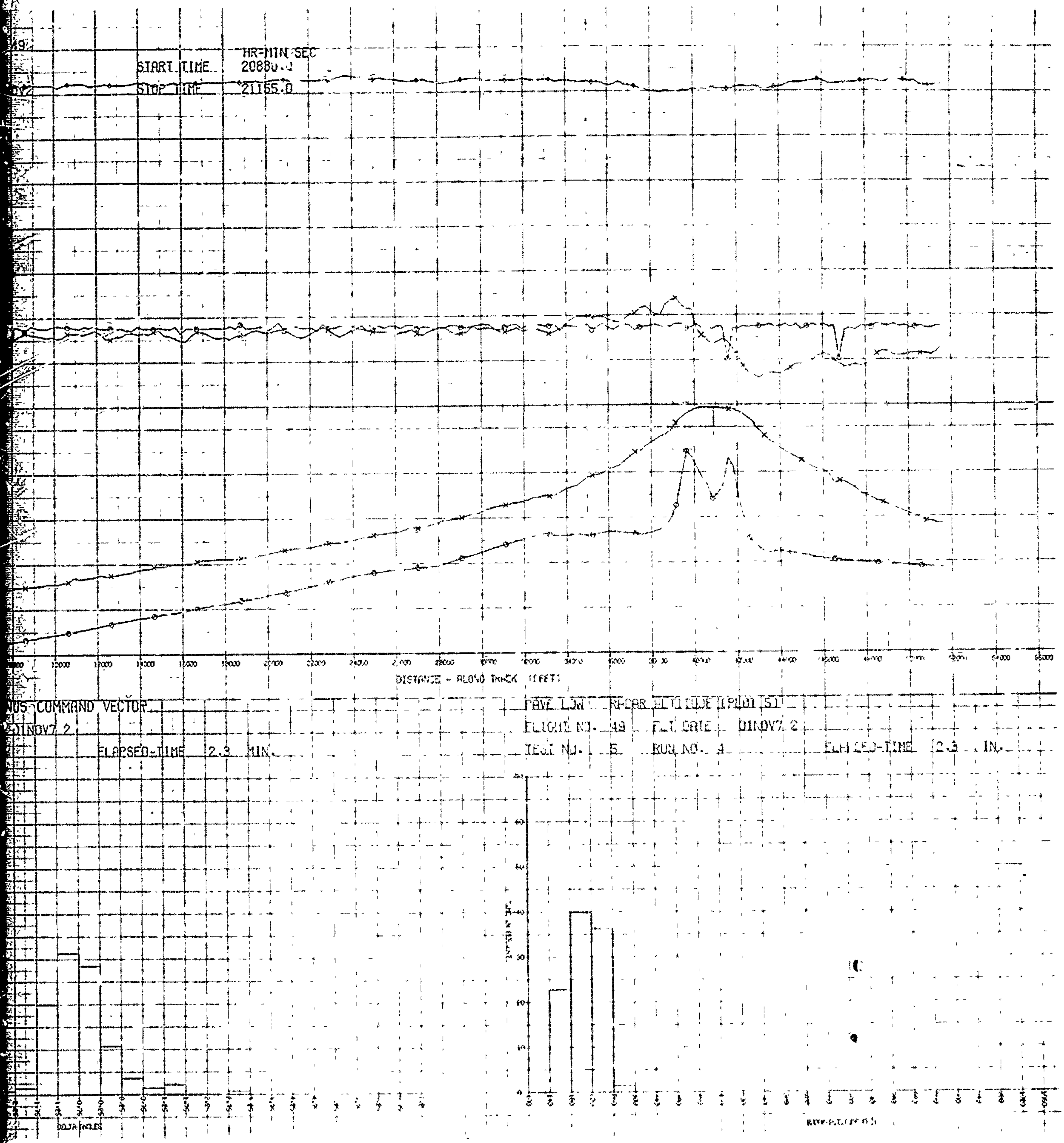
FIGURE 48

2



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND OFF

FIGURE 49



NOMINAL GROUND SPEED 120KTS
COMMAND ALTITUDE 200FT
TERRAIN FOLLOWING COMMAND OFF

FIGURE 49

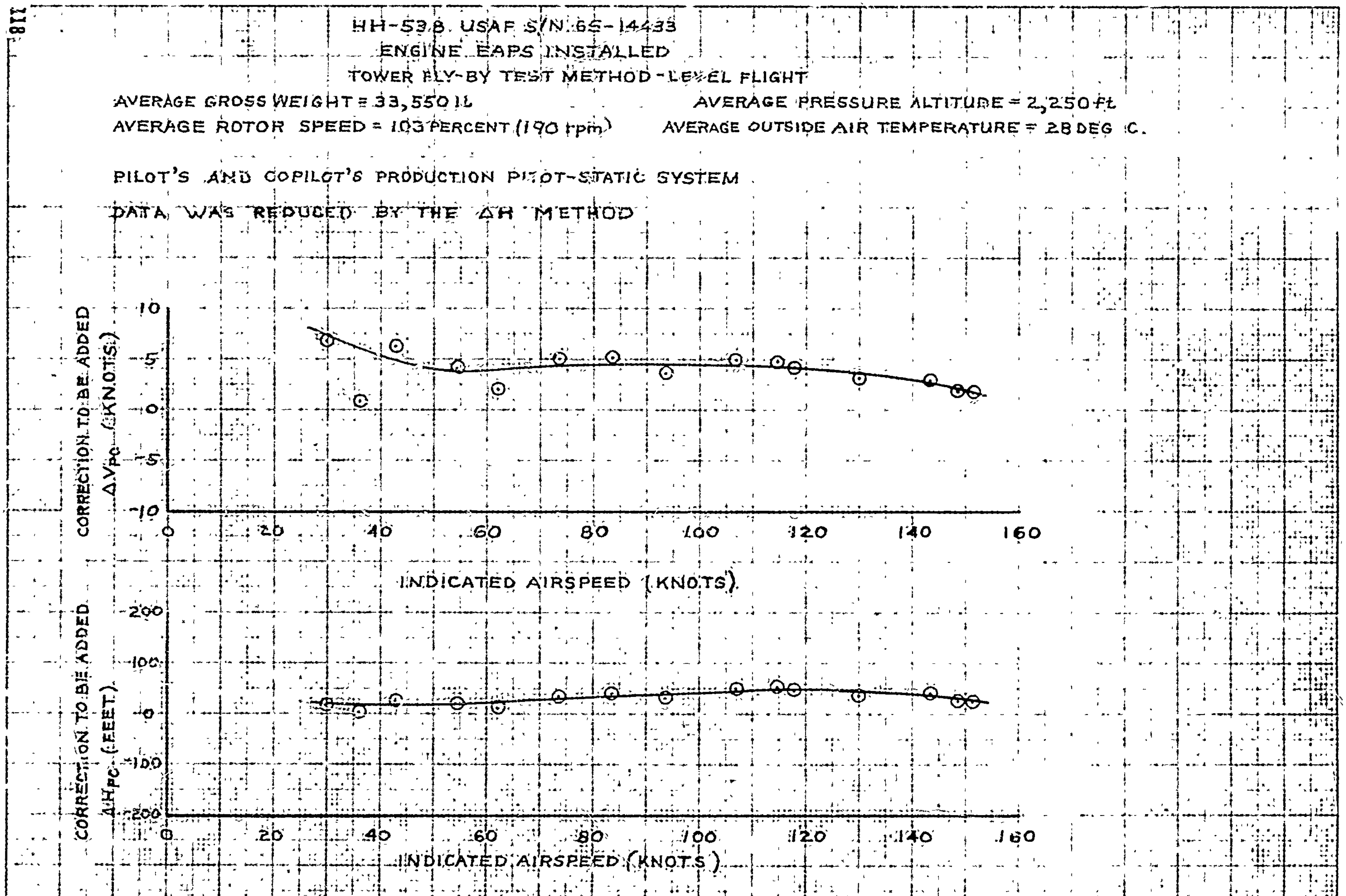


FIGURE 50 AIRSPEED CALIBRATION

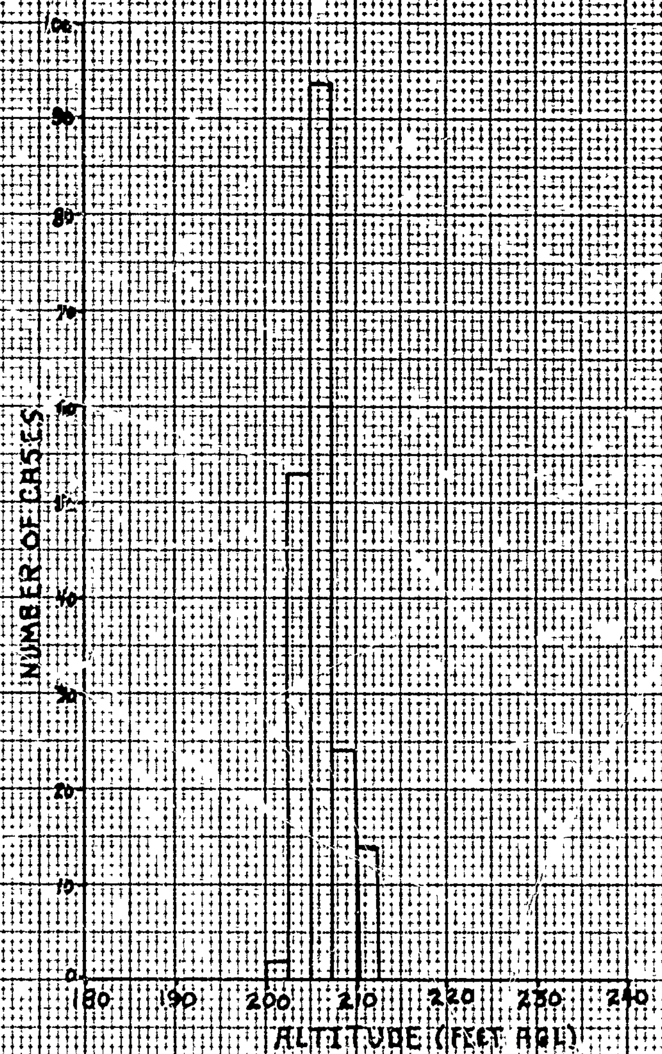


FIGURE 51 COMPUTER PREDICTED ALTITUDE OVER SMOOTH TERRAIN (200 FT AGL)

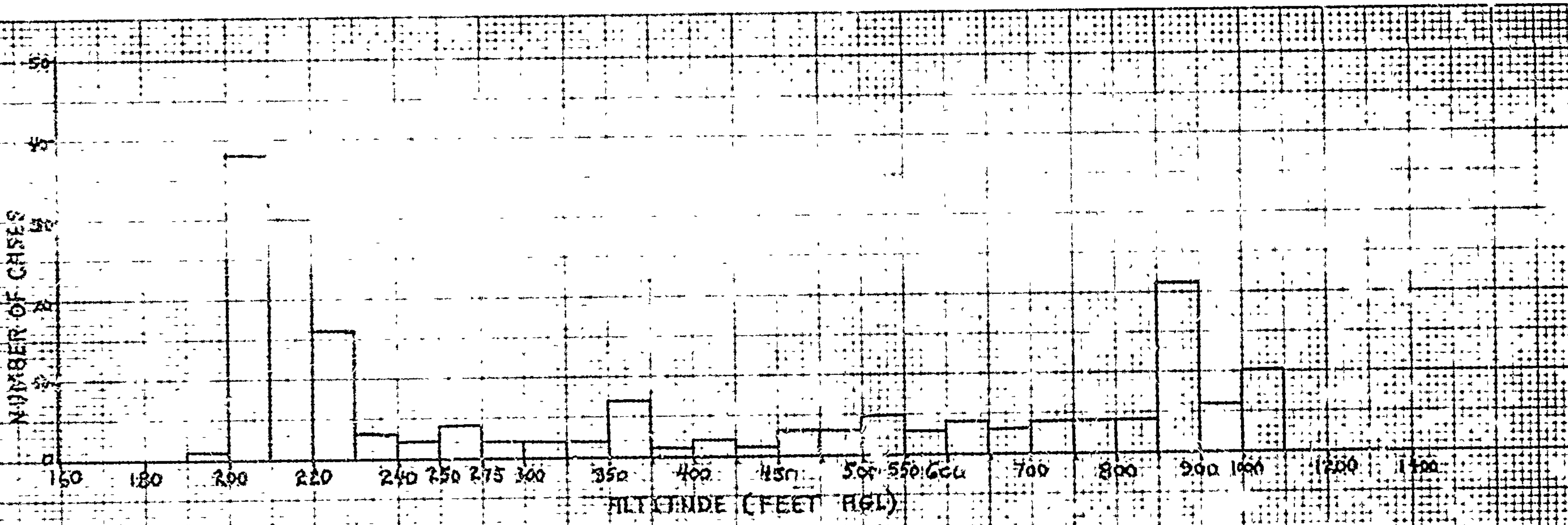


FIGURE 52. COMPUTER PREDICTED ALTITUDE OVER RUGGED MOUNTAIN TERRAIN (200 FT AGL)

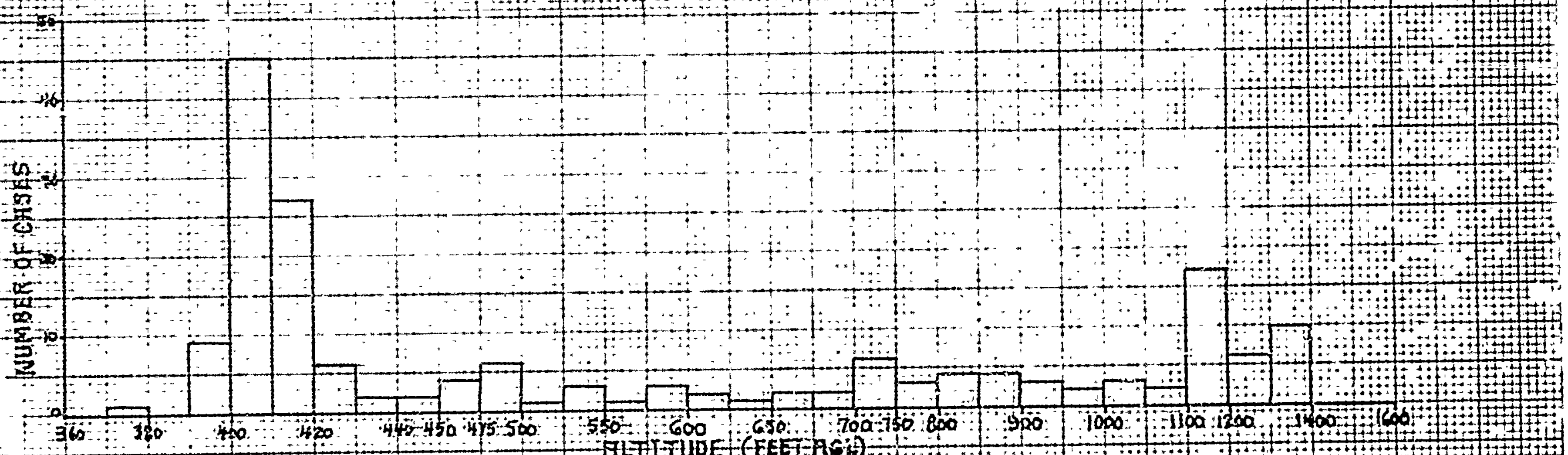


FIGURE 53. COMPUTER PREDICTED ALTITUDE OVER RUGGED MOUNTAIN TERRAIN (400 FT AGL)

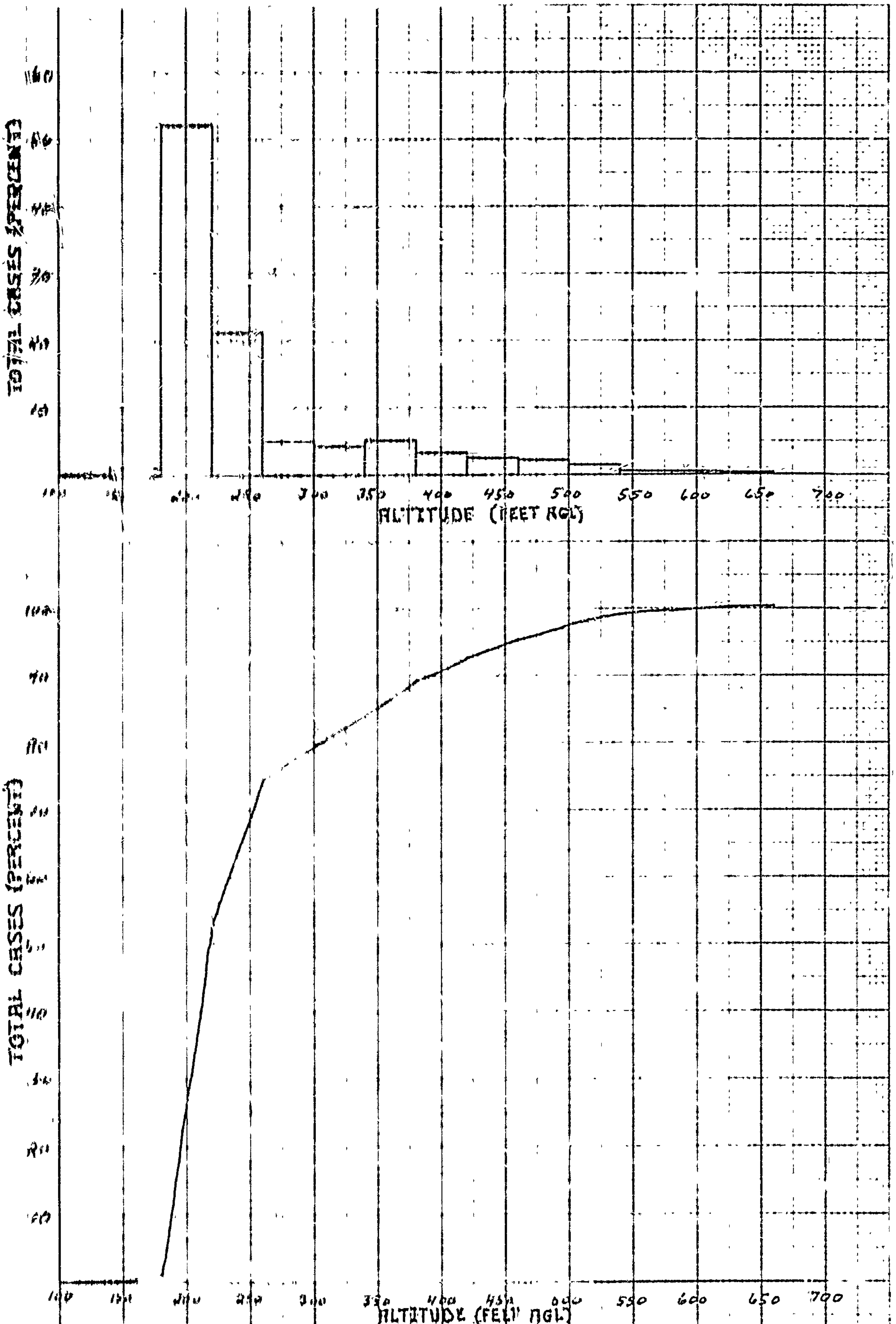


FIGURE 54 CUMULATIVE DISTRIBUTION ALTITUDE OVER MODERATE HILL TERRAIN (100 FT AGL)

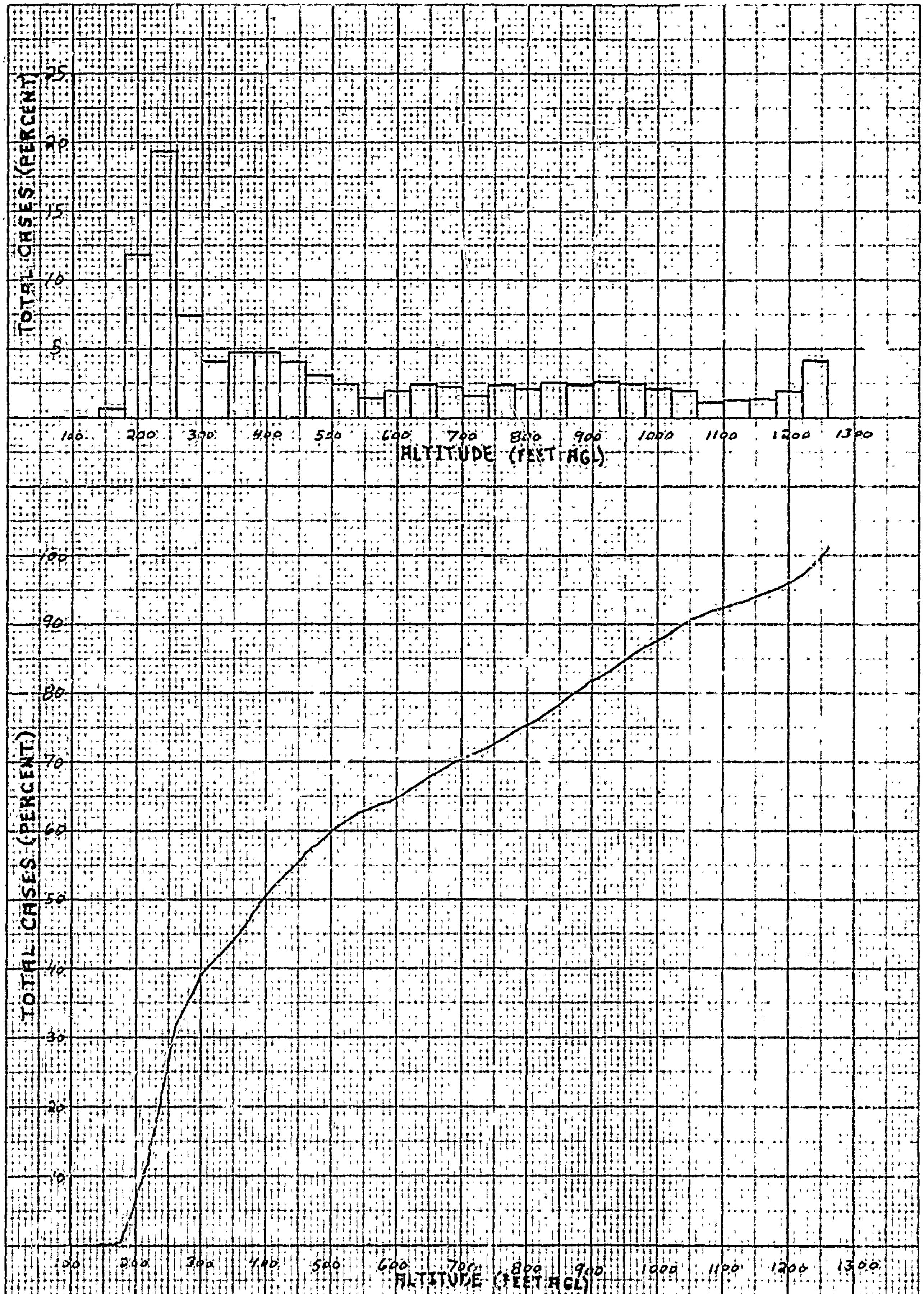


FIGURE 55 CUMULATIVE DISTRIBUTION ALTITUDE OVER RUGGED MOUTAIN TERRAIN (200FT AGL)

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Winter, F.J., Jr., and Schneckenburger, B., Flight Test Evaluation of a Forward Looking Radar System for Search and Rescue Applications, American Helicopter Society, New York, New York, May 1972.

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Richard H. Boivin, Lieutenant Colonel, USAF
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Paul J. Balfe, Major, USAF

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13. ABSTRACT This report presents the results of a flight test and evaluation program of a prototype terrain following/terrain avoidance (TF/TA) radar system for search and rescue applications installed on an HH-53B helicopter. The report also presents an evaluation of the addition of symbology to the low light level television (LLLTV) display installed as part of the limited night recovery system (LNRS) in the same aircraft. The symbology addition to the LLLTV display made a significant improvement to the existing LNRS system. Pilot workload was reduced and the symbology promoted increased pilot confidence and allowed much more precise hover control. The overall impression of the TF/TA radar was that it provided increased capability to perform the night recovery mission. The shades of gray display provided as part of the PAVE LOW program, was exceptionally well suited to the manual terrain following and terrain avoidance mission. However, numerous deficiencies in this preliminary prototype terrain following radar (TFR) system were not corrected because of the limited time and funds available. Among the discrepancies were: insufficient terrain clearance over obstacles, a descent rate that was too slow, insufficient horizontal clearance to obstacles, inability to operate in adverse weather and over certain terrain conditions, and an unsatisfactory failure detection and warning system. Further development and testing is required before a production model system can be achieved.

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